THE INFLUENCE OF TOTAL GAS CONTENT ON THE INCEPTION OF CAVITATION IN A SMALL CENTRIFUGAL PUMP

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PREFACE

Cavitation first became an engineering problem about 1900, when, with the advent of steam turbine machinery and higher propeller speeds, marine engineers noticed losses of efficiency and destruction of propeller materials. Shortly afterwards mechanical engineers in the hydraulic turbomachinery field encountered the phenomenon as speeds of turbines and pumps were increased.

In the last two decades no other phase of hydraulic machinery design and operation has been given so much attention in technical literature as cavitation. Research concerned with cavitation in turbomachines has followed three main lines:

1) Scale model investigations have been used to establish cavitation characteristics in the operating range.

2) The resistance characteristics, under cavitation attack, of materials suitable for use in turbomachines were studied and

3) The physical phenomenon of cavitation, the origin, growth and collapse of bubbles as well as the related mechanism of cavitation damage have been investigated.

Experimental evidence indicates that critical conditions for cavitation depend on a variety of hydrodynamic and non-hydrodynamic effects which complicate the problem of scaling. Among these effects the effect of the total gas content on the inception of cavitation has for long been a subject of intense investigation.

However, whereas there is enough experimental evidence on the way gas content affects the inception of cavitation in venturi-shaped test sections, for turbomachines there is at present no definite experimental evidence on gas content effects on either the initial phase or the developed stages of cavitation.

The purpose of the present work is to investigate the influence of the total gas content of the water on the inception of cavitation in a small centrifugal pump.

The overall accuracy of experimental results on the above field of investigation depends on the accuracy of measuring the actual total gas content of the water. Thus it was thought that a thorough theoretical and experimental investigation on this subject would be of great help in obtaining accurate results and forming a suitable research programme not only for the sake of the present work but also for similar work to be followed by other investigators.

Included in the APPENDICES to the thesis, is a critical survey of the various methods in use for measuring the total gas content, a new method and details of apparatus developed for measuring total gas content, new methods for sampling water for gas content measurements and an experimental study of the deaeration of the water in the circuit used as the cavitation rig, under various rates of flow.

The author wishes to acknowledge his indebtedness to Prof. W.J. Duncan and Dr. A.S. Thom of the Department of Aeronautics and Fluid Mechanics under whose guidance this investigation was carried out and to other members of the staff of the Engineering Department for their assistance in modifying the cavitation rig and carrying out the experimental programme.

He would also like to express his gratitude to Dr. S.P. Hutton, Dr. J.S. Pearsall and Mr. F.A.L. Winternitz of M.E.R.L. for their help and to the Director of M.E.R.L. for the loan of the cavitation rig and accessory apparatus.

He also wishes to express his gratitude to the Dean of the Faculty of Engineering for the permission given to the author to

publish a number of papers appearing in the APPENDICES to the thesis. These papers have been published by the Fluids Division of M.E.R.L.

University of Glasgow.

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A B S T R A C T

The cessation of cavitation as influenced by the total gas content of water has been studied in a small centrifugal pump. The cover of the impeller and the pump casing were constructed of perspex thus allowing optical observation. The water used was tap water. The cessation of caviation in the blades of the impeller was defined optically under stroboscopic light while the pressure in the caviation rig which originally had been brought to a suitable low level was gradually increased. Tests were carried out with the pump operating at various speeds while the flow regulating valve was kept at fixed "opening". In spite of the considerable scatter of the results an almost linear dependence exists between critical pressure for caviation and total gas content. The influence of total gas content on cessation is more pronounced for lower than for higher speeds of the pump.

The results of the present study are in qualitative agreement with that of many previous investigators among whom we mention the works of Numachi, Crump and Shmuglyakov. Whereas a pronounced effect of total gas content was found on the critical caviation conditions, tests on various degrees of cavitation showed no noticeable effect of gas content on developed stages of cavitation.

During the preparation of the small cavitation rig for the present investigation much effort was spent on the detection and elimination of leakages of air into the circuit. Among these leakages the most undesirable was that through the gland of the spindle of the pump. This was stopped by a simple device described in the text.

Included in the APPENDICES to the thesis are 5 papers published by the Fluids division of M.E.R.L. with the permission of the Dean of the Faculty of Engineering. In these are included a critical survey on the various methods for total gas content measurements, the description of a new apparatus constructed and of a new method developed for accurate determination of the total gas content, the development of two new methods for sampling water for gas content measurements and an experimental study of the deaeration of the water in the cavitation rig under various rates of flow.

In the thesis there are also included a short summary of recent opinions on the mechanics of cavitation inception, and a brief classification of the main studies which have been done up to now on the influence of total gas content on cavitation inception. Following the present experimental results a new expression for Thoma's cavitation parameter has been derived which includes the effect of total gas content on the inception.

The calibration of the venturi meter and motor and the performance characteristics of the centrifugal pump have been included in the APPENDICES.

A list of references appears at the end of the thesis.

1. INTRODUCTION

The modern trend in the development of turbomachine design is to cut costs by reducing overall size and weight. In consequence the large water turbines and pumps of today are designed for high specific speeds and high heads which has drastically increased the dangers of cavitation. Winternitz (Ref.1). The undesirable effects of cavitation (loss in efficiency; severe damage of the metallic surfaces) become noticeable only when cavitation takes place beyond a minimum intensity. Cavitation in its incipient form does not noticeably affect the efficiency nor does it cause severe mechanical damage to the metal parts. Nevertheless, an understanding of the mechanics of inception is of material help in understanding the roles of the various factors which influence a variety of cavitation phenomena and effects.

The old assumption that cavitation becomes incipient as soon as the pressure in the minimum pressure region is reduced to the vapour pressure of the water has been proved incorrect. It is by now generally accepted that the critical pressure for the inception of cavitation is not constant and may vary with a number of non-hydrodynamic factors, such as the physical properties of the operating liquid, the condition of the surface of the walls of the container and the solid and gaseous matter contained in the body of the liquid.

Among the above non-hydrodynamic factors the influence of the total gas content on the inception pressure has attracted much attention in the past 20 years. However, whereas there is much experimental evidence on the influence of gas content on the inception of cavitation in venturi-shaped test sections and in

sonically induced cavitation, very little has been published on its influence on the inception of cavitation in turbines and pumps.

The purpose of the present investigation at the University of Glasgow is to study the influence of total gas content on the inception of cavitation in the blades of a small centrifugal pump in a cavitation rig kindly lent to us by the Mechanical Engineering Research Laboratory.

Much of the time spent on the present investigation was used for the development of a more accurate method for measuring the total gas content of the water than the existing methods. Five papers on this subject Kanellopoulos (Refs. 25, 26, 30, 32 and 33) published by the Fluids Division of the M.E.R.L. with the permission of the Dean of the Faculty of Engineering have been included as APPENDICES to the Thesis.

2. MECHANICS OF CAVITATION INCEPTION

2.1. Old assumption for the inception of cavitation:

If the static pressure at a reference point in a hydraulic system were gradually reduced while keeping the rate of flow constant then the pressure head at all points would be decreased. The old assumption for the inception of cavitation was that the inception took place in a hydraulic system as soon as the local pressure in the region of minimum pressure was reduced to the vapour pressure of the water corresponding to the temperature of the experiments. Should the reference static pressure decrease further, the minimum pressure could not drop below that of the vapour pressure. Further decrease in reference static pressure would result in

increasing the rate of vaporization in the regions of flow where the static pressure has dropped to the vapour pressure, i.e. in increasing the intensity of cavitation.

2.2. Modern aspect of Cavitation Inception:

Recent investigations on the inception of cavitation have proved that there is not a definite value for the critical inception pressure. On the contrary it has been shown theoretically and justified experimentally that the inception pressure may vary within a wide range depending on a number of non-hydrodynamic factors. Fresh tap water, for example, cavitates when the local minimum pressure approaches the value of vapour pressure. On the other hand, the same water if it has been previously subjected, even for a short time, to pressurization at a high pressure, may stand considerably high tension (negative pressure) without cavitating.

2.3. Gas Nuclei:

Measurements of the pressure at which vapour cavities form in water have been made under static conditions by applying a steady suction or tension to undisturbed water. Such measurements have resulted in an amazing range of values, ranging from vapour pressure to minus 300 atm. On the other hand, theoretical estimates by physicists, based on calculations of the inherent strength of water, predict even more negative pressures of from -500 to -10,000 atm. for inception. However, such large negative values have never been observed experimentally. To explain why the measured inception pressures are so variable, and always less negative than the theoretical values, it has been postulated that cavitation starts

on microscopic nonhomegeineities, or nuclei in the water. The nuclei are generally assumed to be undissolved gas cavities whose sizes range from 10^{-5} to 10^{-3} inches. The cavitation process is considered to be the growth of these gas-filled nuclei to visible size. The variation of the inception pressure is attributed to variations in the size of these nuclei. Strasberg (Ref. 2)

2.3.1. Stabilization of the gas nuclei:

In water standing undisturbed, free gas bubbles tend to disappear either by dissolving or by rising to the surface depending on the dissolved gas content of the water and bubble size. In water undersaturated with gas, gas bubbles tend to dissolve, the time necessary for them to disappear decreasing quickly for low gas content of water and small original bubble sizes. In supersaturated water, gas bubbles will grow by diffusion of gases dissolved in the water surrounding the bubble, and will rise to the surface with a velocity which will be larger for larger size of the original bubble and higher degree of supersaturation.

Accordingly, if bubbles are to persist in water, it is necessary that new bubbles be formed continuously, or else some mechanism must prevent them from dissolving or rising.

In circulating hydraulic systems and water supersaturated with gases several mechanisms may prevent bubbles from disappearing Strasberg (Ref. 2). However, if the water is undersaturated with gases nothing could prevent free gas bubbles from dissolving. Thus, water undersaturated with gases should be completely free of such gas bubbles.

Nevertheless, cavitation certainly does occur in undersaturated water, indicating that nuclei are indeed present. Moreover,

there is convincing evidence that nuclei contain gases. Perhaps the most convincing evidence is the demonstration of Harvey et al (Ref. 3) that water cannot be made to cavitate after it is temporarily subjected to a high pressure; the only explanation of this phenomenon, is that the gas nuclei are removed as the high pressure forces them into solution.

Accordingly, cavitation theory is faced with the following dilemma: the results of measurements and theory indicate the presence of undissolved gas nuclei in undersaturated water, yet diffusion theory indicates that free nuclei should spontaneously disappear by dissolving in the water.

To resolve this dilemma two alternative mechanisms have been suggested for the stabilization of gas nuclei.

i) Minute undissolved volumes of gas may be stabilised in very small crevices on the container or circuit walls and/or in crevices on the surface of solid particles suspended in the water. Harvey et al (Ref. 4)

ii) Organic impurities existing in the water and causing a monomolecular film around gas bubbles may prevent the solution of such stabilized gas bubbles. Fox & Herzfeld (Ref. 5)

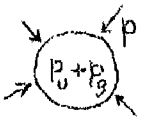
For the formation of such minute gas volumes Harvey et al (Ref. 4) has suggested that thermal fluctuations can initiate a bubble within a conical crack contained by solid suspensions and that gas from the surrounding liquid would diffuse into the bubble and stabilize it.

2.3.2. Growth of the gas nuclei. Critical pressure for the inception of cavitation:

It is now generally accepted, Eisenberg (Ref. 6) that cavita-

tion in a liquid under reduced pressure begins with the growth of gas nuclei stabilized in the liquid by either of the mechanisms described above. The nature and size of the nuclei determines the critical pressure for the inception. Growth of a bubble may be "explosive" by vaporization or slow by gas diffusion. To distinguish between the growth of a bubble by vaporization and by the diffusion of dissolved gases into the bubble, Blake (Ref. 7) defined these two processes as "vaporous" and "gaseous" cavitation and examined the conditions under which each would occur. Based on these results, Strasberg (Ref. 8) has shown that, while, for vaporous cavitation, pressures equal to or less than vapour pressure are always required regardless of initial nucleus size, pressures either above or below vapour pressure can initiate gaseous cavitation depending on initial radius and partial gas volume.

The inception of cavitation is referred to the conditions within the liquid under which the first bubbles start to grow almost explosively. The so-called gaseous cavitation results from a different phenomenon to which the name "rectified diffusion" has been attached. The condition of stable mechanical equilibrium of a bubble is given by the following relation:



$$p_g + p_v = p + \frac{2\tau}{R} \qquad (2.3.1)$$

where p_g is the partial pressure of gas in the bubble

p_v is the vapour pressure

p is the pressure in the liquid surrounding the bubble

τ is the surface tension

and R is the bubble radius.

For a bubble containing a given amount of gas there exists a minimum external pressure ($p = p_c$) below which static equilibrium cannot be

maintained. If the external pressure were reduced below p_c then the bubble becomes unstable and grows without bound at a rate limited by the inertial reaction of the surrounding liquid.

This pressure is called the critical pressure and is given by the following relation Strasberg (Ref. 8).

$$p_c = p_v - \frac{2}{9}\sqrt{3}\left[\frac{2\tau}{R_o}\right]\left[1+(p_o - p_v)\frac{R_o}{2\tau}\right]^{-1/2} \quad \ldots \quad (2.3.2)$$

where

Ro is the initial radius of the bubble under external pressure of the surrounding liquid p_o.

It seems from the above equation that as Ro increases p_c also increases, i.e. the critical inception pressure increases. Stated otherwise conditions become more favourable for cavitation to start in waters containing larger nuclei. If the water originally contained bubbles of about Ro=0.01" diam. under atmospheric pressure (p_o = 1 atm) the critical pressure would be only 0,01 ft. of water below the vapour pressure; while if Ro=0,0001" under p_o = 1 atm. the critical pressure would be about 10 ft. of water below the vapour pressure.

If the original radii of bubbles in the liquid were smaller than that required for a bubble to undergo vaporous cavitation under a given minimum pressure then according to the theory cavitation would not take place.

It is possible, however, that a nucleus originally too small to undergo vaporous cavitation (explosive growth) at the existing pressure could grow by gas diffusion until it became large enough to go into vaporous cavitation. Strasberg (Ref 2).

The growth of bubble by gas diffusion depends on the amount of gases dissolved in the water and on the time of exposure of the

bubble to water supersaturated with gas. Thus for nuclei of a given original size the longer the time of this exposure the higher the expected inception pressure.

In connection with the above vaporous-gaseous interaction Daily (Ref. 9) suggests that the most probable sources of nuclei for cavitation inception in circulating water are the minute volumes of gases trapped in crevices in the boundary walls of the low pressure region. As the pressure is reduced, microscopic gas volumes in these crevices expand isothermally; this expansion is augmented by diffusion of gas into the small cavity. As this volume increases, a small bubble begins to emerge from the boundary. This bubble becomes subject to the lift and drag of the high velocity flow past the boundary and is swept off and carried downstream by the flow to a zone of lower pressure where it becomes unstable and the phenomenon of cavitation occurs. After a bubble is swept off, some gas remains in the crevive to repeat the process.

On the other hand, nuclei trapped in crevices on suspended solid matter in the bulk of water have a much shorter time interval to grow by diffusion of gases from the supersaturated liquid as the stabilized nuclei pass through the region of low pressure.

Daily (Ref. 10) also states that although measurements of the critical inception pressure in various experiments indicate that the pressure at inception is above vapour pressure, this cannot be, and that some unmeasured negative pressure increament must have existed which caused the net pressure to be below vapour pressure. He considers that this negative pressure increament is caused by the pressure drop associated with the vortical eddies composing the turbulent boundary layer.

3. INFLUENCE OF TOTAL GAS CONTENT ON THE INCEPTION OF CAVITATION

There is now enough experimental evidence that the total gas content of water circulating under ordinary experimental conditions does affect cavitation inception. The lower the value of total gas content the lower are the inception pressures, or the less favourable are the conditions for cavitation to start. The exact mechanism by which the total gas content affects the inception pressures has not been completely explained. Nevertheless, the author's opinion is that its influence on the inception of cavitation should be associated jointly with its influence on the density of population and statistical size of gas nuclei and on the growth of these nuclei to become the source of the cavitation inception.

If all the other conditions in the circulating liquid - which would probably affect the inception - could be kept constant, then the higher the total gas content the greater would the size of the gas nuclei be expected, and consequently, the higher the pressures under which the cavitation would become incipient. However, some of these conditions can not be controlled and so there is a considerable amount of scattering in the experimental relations between the incipient pressures and total gas content of the water.

The effect of total gas content on cavitation had been well recognized before but the most fundamental approach to its influence on the inception of cavitation must be considered to be the work of Numachi (Refs. 11 - 14) in 1938 and 1939.

Since then much experimental work has been done on this subject. To summarise the results of the main works on this it is convenient to classify them in three categories.

i) Studies of the effect of gas content on inception in venturi

nozzle test sections.

ii) Studies of the effect of gas content in sonically induced cavitation.

and iii) Tests on the influence of gas content on the inception of cavitation in turbomachines.

i) The effect of gas content on the inception of cavitation in venturi nozzle test sections:

Most of the works on the influence of total gas content on the inception of cavitation is in this category. Among these works the following should be mentioned:

a. Numachi (Refs. 11 - 14).

Numachi and Numachi and Kurokawa have made a thorough investigation on the appearance of cavitation in different kinds of water (distilled, salt and sea water) and for several shapes of glass venturi-nozzle and hydrofoil. Using a miniature non-circulating water tunnel constructed entirely of glass Numachi measured the velocity and the pressure at the entrance to the diffuser under the conditions at which cavitation first appeared (optical method for the detection of the inception of cavitation).

In all his tests Numachi found that for any kind of water the amount of gas dissolved had a significant effect on the value of the critical pressure at which cavitation started. He found that the greater the amount of dissolved gases the higher the pressure at which cavitation at first appeared.

Incipient cavitation for a given value of gas content and nature of water appeared not at a definite point but throughout a definite zone. The extent of this zone was comparatively small for high gas contents while it increased rapidly as the gas content

was reduced.

For the same value of gas content and the same temperature of the experiments Numachi found that sea water started cavitating at higher pressure than salt water which in turn started cavitating at higher pressures than distilled water. The influence of gas content was found to be more pronounced in distilled than in salt water, and in sea water less pronounced than in salt water.

In parallel with the influence of gas content he studied the influence of velocity and temperature on the inception of cavitation and extended his experiments on developed stages of cavitation.

Although, due to the very large scatter, the results of Numachi are rather of a qualitative mature, they provide enough evidence that there is no definite value for the critical inception pressure.

b. Crump (Refs. 15 - 16)

Crump in his experiments used a portable closed-jet water tunnel which could be operated on either a recirculatory or non-recirculatory basis. He adopted the optical method for detecting the inception of cavitation. Although the absolute values of the critical pressures for the inception of cavitation in a 12-scale model of a Numachi nozzledo not agree with that of Numachi the same general trends were observed. Crump suggests that the observed differences are due to vortex formation in the diffuser and Reynolds number effects.

c. Ziegler (Ref. 17).

Ziegler used a closed hydraulic circuit with a venturi-shaped test section. The inception of cavitation was detected optically, acoustically and by means of a highly sensitive electrical vibration measuring device. His results showed that for high gas contents

inception took place at vapour pressure. At lower gas contents it was necessary to reduce the pressure below vapour pressure in order to obtain any bubble formation.

d. Williams (Ref. 18) and later Pearsall (Ref. 19).

worked on the same experimental circuit the working section of which consisted of a small 2 - dimensional venturi-nozzle (diffuser) with a divertor placed in the centre of the stream. The inception of cavitation was detected acoustically using a Rochelle salt hydrophone feeding into an amplifier, and thence to a voltometer. Distilled water was used as circulating liquid, and various strengths of water-sodium nitrate solutions. They both found no appreciable relation between total gas content and inception of cavitation pressures. Nevertheless, a slight decrease in inception pressures was observed for smaller gas contents. The inception pressure under the same conditions was found to be greater in water-sodium nitrate solutions than in distilled water, and the higher the concentration of sodium nitrate the higher the inception pressure.

ii) Studies of the effect of gas content in sonically induced cavitation:

Large local reduction of pressure in the body of standing liquid may be realised when a sound field of appropriate intensity is set up in the liquid. By adjusting the intensity of the sound field the liquid can be made to cavitate. Measurements of the sound field intensity can be transformed in terms of pressure in the focus of the sound field where cavitation bubbles first appear.

One of the advantages of the acoustic method of inducing cavitation is that through focussed waves the onset of cavitation can be studied away from container walls and within the body of a

liquid. The elimination of wall effects facilitates the measurement of acoustic cavitation thresholds as a function of independent variables such as temperature, hydrostatic pressure, and gas content Bouyoukos (Ref. 20).

In the past decade much work has been done using the present method for the determination of the cavitation threshold as it is influenced by various factors among which the total gas content has attracted much attention. Among these works the following are mentioned:

a. Blake (Ref. 7)

Blake in his summary concludes:-

"The threshold pressure for cavitation depends inversely upon nucleus size. The equilibrium gas content of a nucleus increases as the dissolved gas content of the liquid increases, as the temperature increases, and as the hydrostatic pressure decreases." Accordingly under the same conditions of temperature and hydrostatic pressure the higher the gas content the higher will be the expected pressures for the cavitation threshold.

The importance of Blake's statement should be emphasized here. It not only describes the influence of gas content on inception pressures but suggests also a possible mechanism of the way in which the total gas content affects the cavitation inception.

b. Strasberg (Ref. 2)

Strasberg states that from theoretical calculations of the critical pressure for vaporous cavitation with either of the mechanisms for the stabilization of nuclei (nuclei trapped in cracks on the surface of solid particles suspended in the water, or organic skin on the surface of the gas nuclei) the functional

relationships are of the same form.

$$p_c = \alpha_1 G - \alpha_2 p_m \quad \ldots\ldots (3.1)$$

where

p_c is the critical pressure for the inception of cavitation.

G is the equilibrium or saturation pressure of the gas dissolved in the water (Henry's Law)

p_m is the maximum external water pressure to which the cavity (nucleus) has been subjected.

and α_1, α_2 are numerical constants, whose values cannot be determined with present knowledge, except that

$$\alpha_2 + 1 > \alpha_1 > \alpha_2 > 1 \quad \ldots (3.2)$$

Equation (3.1) indicates that the critical pressure should decrease linearly with decreasing equilibrium gas pressure (or otherwise, with decreasing dissolved gas content). The linear variation of inception pressure with gas content, predicted by equation (3.1), is verified by his experimental data.

Strasberg, in accordance with the statement of Blake, concludes that the definite variation of inception pressure with gas content indicates that the nuclei are not solid particles alone, but rather gas cavities whose size depends in some way on the dissolved gas content.

c. Cheng (Ref. 21)

Cheng in personal communication with the author states: "Cavitation threshold in tap water depends on the air content, solid nuclei in suspension or contamination and the maximum pressure to which it has been subjected. The transition from gaseous to vaporous cavitation takes place at about 50 per cent. air saturation. Within this region the two types of cavitation

may occur separately or simultaneously. Both types of cavitation show a dependence on the above mentioned factors and within the region where only one or the other is occurring the threshold for both types shows a linear variation with air content for one batch of water.

The addition of wetting agent considerably increases the threshold of both tap and distilled water."

iii) Tests on the influence of gas content on the inception of cavitation in turbomachines:

Whereas much experimental data on the influence of gas content on the inception of cavitation exists for venturi-nozzle test sections and sonically induced cavitation, very little experimental evidence exists for similar tests in turbomachines. The only works - to the author's knowledge - which have been reported on this field are those of Vuskovik (Ref. 22) and Shmuglyakov (Ref. 23).

a. Vuscovic concludes that the quantity of dissolved gas has hardly any effect on the critical value of the cavitation coefficient σ (Thoma's cavitation parameter).

b. Shmuglyakov has carried out a number of tests on various turbine models, to study the effect of dissolved gas on the inception of cavitation. The critical value of the cavitation coefficient was determined by the abrupt change in the cavitation characteristics of each turbine.

The tests were carried out on models 400 mm diam., in a horizontal closed rig. Four operating regimes of each turbine were investigated in detail. Each regime was characterised by constant head, "opening" and load; tests were done with water in which the gas varied from 0.26 to 1.66% free air volume relative to the water

volume (i.e. 12% - 80% of the gas content of water saturated under atmospheric conditions at 20°C.)

The data of his work show that the value of the critical cavitation coefficient depends on the amount of gases dissolved in the water and its value increases with increase of gas content, or alternatively, for higher gas content the greater is the danger of cavitation starting.

c. Tests on the inception of cavitation were carried out, by the author, on a small centrifugal pump. The experimental rig was lent to Glasgow University by M.E.R.L. and is the same as that used by Williams (Ref. 18) and Pearsall (Ref. 19) for their experiments on the inception of cavitation in a diffuser test section. The experimental procedure and results are described in detail later. Cavitation cessation was detected optically.

In all the tests, in spite of a considerable scattering of the results, a definite variation of the critical cavitation parameter with changes in gas content was found to exist. At constant speed of the pump and "opening" of the flow regulating valve the higher the gas content the higher the value of the critical cavitation parameter. The influence of gas content was found to be more pronounced for lower speeds than for higher speeds of the pump.

Concluding Remarks:

The influence of the total gas content of the water on cavitation has been the subject of intense investigation during the past decade. Although the definition of the inception may vary for the various methods and among the various investigations, there is enough experimental evidence to conclude that the total gas content does affect the inception pressures in the ordinary liquids used in

hydraulic laboratory applications. The results of these experiments have proved incorrect the elementary assumption that cavitation starts when the minimum pressure in the liquid drops to the vapour pressure. Inception of cavitation is connected intimately with the growth of gas nuclei existing in the water. Inception pressures increase with increase of the equilibrium size of stabilized gas nuclei. In turn both the equilibrium size and growth of nuclei are strongly affected by the amount of dissolved gases. The scattering of the experimental results plotted as diagrams of inception pressures against total gas content can be explained by the statistical distribution of the equilibrium size of the gas nuclei.

The growth of gas nuclei which takes place by a diffusion process will also be a function of the geometry of the particular experimental circuit. To illustrate this let us follow the path of an individual gas nuclei of given original size. (FIG. 3.1.)

Let α_t be the mean dissolved gas content of the water in the circuit at time t;

p_e be the pressure of the liquid surrounding the bubble at time t;

and let α_e be the dissolved gas content of water saturated at pressure p_e

Then the ratio $\frac{\alpha_t}{\alpha_e}$ represents the degree of saturation or under-saturation of the water surrounding the bubble along its path. The value of $\frac{\alpha_t}{\alpha_e}$ compared with unity will control the direction of the exchange of gas between the undissolved (gas bubble) and dissolved state. If $\frac{\alpha_t}{\alpha_e} > 1$ gas will diffuse out of the solution into the bubble while for $\frac{\alpha_t}{\alpha_e} < 1$ the reverse process

will take place.

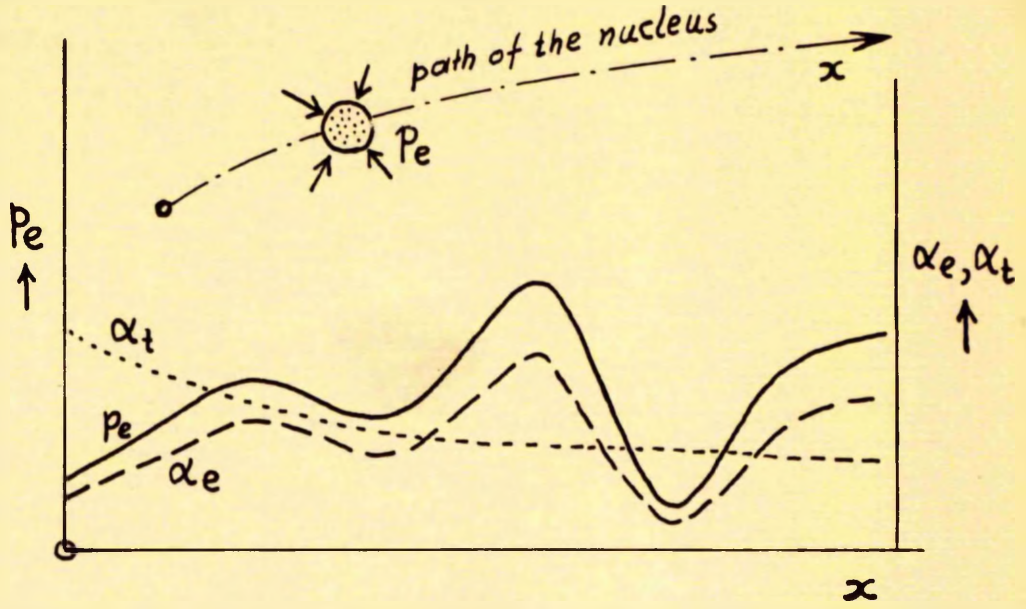


Fig. 3.1. Variation of p_e, α_e and α_t along the path of a nucleus

The absolute magnitude of this exchange of gas between the dissolved and undissolved state will be controlled by the gas content of the water (α_t) and the time variation of the ratio $\frac{\alpha_t}{\alpha_e}$ along the path of the bubble.
Finally the size of the bubble will depend on its gas content and the static pressure of the surrounding water.

It should be emphasized, however, that the influence of total gas content on the inception of cavitation depends greatly on the geometry of the flow of the experimental circuit (size of various parts of the circuit, velocity of flow, pressure gradients) used, and this may be the reason why the experimental results of the various investigators in this field do not agree absolutely.

In spite of the experimental evidence that total gas content does influence the inception pressures there is still some controversy Eisenberg (Ref. 24). The main argument is that standing,

freshly deneucleated water does not cavitate even if it is saturated with air. But all these requirements are never fulfilled by the water in ordinary experimental circuits. Gas nuclei are always present and their equilibrium size and growth are intimately associated with the dissolved gas content of the water.

4. TOTAL GAS CONTENT OF WATER IN HYDRAULIC CIRCUITS

4.1. General:

The total gas content of the water in hydraulic circuits is the sum of the dissolved gas, gas nuclei and entrained gas contents. Although exact experimental results for the gas nuclei content of the water do not exist, it is believed to be a very small fraction of the total gas content. Thus if all possible care has been taken to eliminate leakages of atmospheric air into the circuit, the dissolved gas content represents almost the total present in the water.

The gaseous mixture in water-gas solutions used in hydraulic applications consists of three main gases, namely nitrogen, oxygen and carbon dioxide.

The general principles governing and the factors affecting the solubility of gases in liquids have been summarised by Kanellopoulos (Ref. 25)

The total gas content of the water may be expressed as the concentration (c) of gases in the water, usually given as c ..mg of gas per litre of water, or as the volume of gases (α or V^*) released from a given quantity of water and reduced to N.T.P.

α or V* represents cm^3 gas at N.T.P. per litre of water.

Another form which is often used for expressing the magnitude of the total gas content is the ratio of the actual gas content to that of water saturated under atmospheric conditions and at temperature $20^{\circ}C$, symbolised by $\frac{\alpha}{\alpha_s}$

Where α is the actual gas content of water.

and α_s is the gas content of water saturated with air under atmospheric pressure and temperature $20^{\circ}C$.

In the literature on cavitation some writers associate the terms undersaturation and supersaturation with the values of the ratio $\frac{\alpha}{\alpha_s}$. They often write "undersaturated water" when $\frac{\alpha}{\alpha_s} < 1$ and "supersaturated water" when $\frac{\alpha}{\alpha_s} > 1$. This is wrong because the terms "supersaturation" and "undersaturation" should denote deviations of the gas-water solution from an equilibrium condition (i.e. saturation). This equilibrium is a function of the temperature and pressure in the solution. If the temperature of the solution were kept constant, then, for any presssure (p_o) there is an equilibrium gas content (α_o) given by Henry's Law:

$$\frac{\alpha_o}{p_o} = \text{constant} \quad \text{---------- (4.1.1)}$$

Thus for a given temperature and pressure (p_o) the solution (gas content α) will be undersaturated if $\frac{\alpha}{\alpha_o} < 1$ or supersaturated if $\frac{\alpha}{\alpha_o} > 1$.

4.2. A critical survey of the various methods for measuring the total gas content of water. Kanellopoulos (Ref. 26)

This theoretical investigation is described in detail in APPENDIX I. A brief summary of this study is presented here.

The total gas content in water influences several of its

physical properties such as its density, compressibility, surface tension, tensile strength, conductivity, refraction index, light absorption and inception of cavitation. However, change of most of the above physical properties of the water with change in its gas content is either very slight or depends mainly on the composition of the dissolved gaseous mixture.

The various methods which have been used or have been suggested for the determination of total gas content have been classified under two categories: a) the direct and b) the indirect methods.

a. Direct methods:

In any of these methods the total gas content of a sample of water is extracted from the solution by subjecting the sample to a vacuum (of the order of the vapour pressure of the water) and repeatedly spraying or continuously shaking it. Then the pressure of the released gases constrained in a given volume is measured. The amount of released gases referred to N.T.P. represents the total gas content of the sample. These methods are also known as extraction methods. Each requires apparatus simple to construct and operate. Such methods have been developed by Van Slyke (Ref. 27), Williams (Ref. 28), Shal'nev (Ref. 29) and lately by the author (Ref. 25, 30.)

b. Indirect Methods:

Under this category are included all the methods which are based on measurement of the amount of one of the gaseous constituents dissolved in the water. The corresponding total gas content is afterwards found by calculation. Application of the indirect method is, for example, the Winkler (Ref. 31) chemical

method of computing total gas content from determinations of the dissolved oxygen content.

On the basis of a number of simplified assumptions the variation of the composition of the dissolved gaseous mixture with total dissolved gas content has been studied theoretically. It was found that this composition varies with the total amount of gases dissolved in the water and that this composition depends also on whether the total dissolved gas content approaches a fixed value from higher or from lower gas contents (i.e. it depends on the process : aeration or deaeration).

It is shown also that for water in hydraulic circuits deviations from the simplified assumptions should be expected, and that such deviations would result in further complicated and irregular variations in the composition of the dissolved gaseous mixture.

The result of this analysis is that there is not a definite (fixed) variation in the composition of any of the constituents of the dissolved gaseous mixture and, therefore, the use of the indirect methods for the determination of total gas content would lead to a very poor accuracy especially with water samples of low gas contents.

So far the only reliable methods for measuring the total gas content are the extraction methods.

4.3. New method for measuring the gas content of the water.

Kanellopoulos (Ref. 25)

This publication has been included in the APPENDICES to the Thesis (APPENDIX II).

The present method, which is an extraction or direct method, has been developed as part of the research programme and was used for measuring the gas content of the water during the experiments on its

influence on the inception of cavitation in a small centrifugal pump.

The principle of operation of the new apparatus is similar to that of M.E.R.L., Williams (Ref. 28) which itself was an improvement of the Van Slyke (Ref. 27) apparatus. The alterations made include modifications to the spraying chamber and changes to other parts which have resulted in greater ease of handling and quicker speed of operation.

The present apparatus is accurate within the limits $\pm$ 1% for water saturated with air under atmospheric conditions, i.e. for water with high gas content. As follows from the detailed theoretical analysis, however, the accuracy of this method is expected to be about the same over the whole range of gas contents with a slight deterioration for very low gas contents due to the effect of systematic errors.

Following the theoretical analysis the derivation of a simplified formula for the accurate calculation of the total gas content of a sample of water is considered and the simplified formula is provided at the end of this work.

Although the analysis of errors has been worked out for the M.E.R.L. apparatus and is thus referred to in the report, it applies equally well to all other gas content meters of the extraction type (e.g. Van Slyke, Shal'nev), which are all subject in a greater or lesser degree to these errors and corrections.

4.4. Errors in Measuring the gas content of the water:

Kanellopoulos (Ref. 30).

This theoretical investigation is described in detail in APPENDIX III.

It is a continuation of the previous report, and involves the assessment of errors in the extraction methods.

Among the various errors which are discussed in the previous work is the error which results by assuming that the sample of water is completely deaerated after the spraying process.

With the method described in 4.3. of APPENDIX II it was found that the sample was not completely deaerated after the spraying and that water samples originally saturated with air were found to contain 4 per cent of the original gas content. Then in the derivation of the simplified formula for calculation of total gas content it was assumed that the gas content remaining in solution after completion of the spraying process would be 4 per cent of the original over the whole range of gas content.

Shortly after the publication of the previous report the author found that the above assumption was not correct. The deaeration of a water sample originally saturated with air under atmospheric conditions was studied considering the gases dissolved in the water not as a single gaseous component, as has often been wrongly done, but as consisting of a mixture of three main gases namely N_2, O_2 and CO_2. As can be seen from FIG. 2 of this APPENDIX the rate of deaeration decreases gradually as the gas content of the water decreases.

The curve in FIG. 3 (APPENDIX III) represents the variation in the percentage of the amount of gases left in solution after the spraying process as a function of the original gas content of the sample. This percentage increases rapidly for low gas contents.

Following the results of the present work the analysis of

errors of the previous work has been completed and corrected and a new simplified formula for the calculation of total gas content has been derived.

4.5. Methods of taking samples of water for measuring the gas content. Kanellopoulos (Ref. 32)

This subject is discussed in detail in APPENDIX IV.

The accuracy of the estimation of the total gas content of water in hydraulic circuits is not only limited by the accuracy of the gas content meter used but also depends on the method of sampling the water. The method of sampling may affect the accuracy of gas content measurements by providing in the gas content apparatus samples whose gas contents may be altered during the sampling process. It is then possible for the measured gas content to be higher or lower than the real gas content of the water in the circuit.

The various methods used for taking samples of water out of the circuit and their disadvantages are discussed in detail in the present work. The suitability of all these methods was found to be limited, and to depend on such conditions in the circuit as the static pressure, amount of gases dissolved in the water and area of free surfaces.

In his attempt to provide a reliable method for sampling water under any condition in his cavitation circuit, the author developed two new methods of sampling. These methods are described in detail under the headings "Method A" and "Method B."

The great advantage of "Method B" is that it can provide truly representative samples under any condition in the circuit and therefore it may be universally adopted as a method of sampling.

5. VARIATION OF TOTAL GAS CONTENT IN THE CAVITATION CIRCUIT

Kanellopoulos (Ref. 33)

Preliminary tests on the influence of total gas content on the inception of cavitation in the centrifugal pump indicated that the deaeration of the water took place much more quickly than was expected.

The total time necessary for adjusting the circuit to the desired conditions, taking the sample of water and measuring the gas content was never less than 10 minutes. In such an interval of time it was noticed that the gas content could drop down to 50 per cent. of its original value depending on the conditions of gas content, pressure and rate of flow in the circuit. This imposes some limitations on the range of gas content in which experiments on cavitation may be carried out.

In order to prepare a suitable research programme which would have as short an experimental time as possible, it was thought that the actual deaeration of the water in the circuit should be systematically investigated.

The results of this investigation are presented in APPENDIX V.

The water used in connection with these experiments was tap water. The deaeration of the circuit was tested for 2800, 2500, 2000, 1500 and 1000 rev./min of the centrifugal pump as well as with the pump nominally stopped. In all these tests the flow regulating valve was kept constantly at its fully open position, while the static pressure in the gaseous space of the tanks was kept as nearly constant as possible ($\sim$ 5.0 ft. of water abs.press.)

The experimental results show that the rate of deaeration

increases rapidly as the speed of the pump is increased. The variation of gas content against time of deaeration may be represented by mathematical formulae. The agreement between the theoretical curves and experimental ones is very good.

Accordingly an attempt has been made to explain how the deaeration of the water in the circuit takes place. For that a study has been made of the deaeration of the water in the present tunnel on the assumption that the release of gases takes place only through the free surfaces of the water in the two tanks. Under this assumption the calculated rate of deaeration is much smaller than any of the actual rates of deaeration. This suggests that another additional area of gas-water interface exists in the body of the water. In stationary water this additional gas-water interface is due to the presence of undissolved gas nuclei in the body of the water while in circulating water under low pressure, except for the nuclei content, the gas-water interface increases with the intensity of cavitation. A rough calculation shows that when the circuit is static the total gas-water interface must be 5 times the surface of the cross-section of the tanks while for a pump speed of 2800 rev./min the total gas-water interface required to justify the great rate of deaeration should be as high as about 50 times the surface of the cross-section of the tanks.

A paragraph of the work referred to is devoted to the aeration of the water and to the reabsorption of travelling gas bubbles in the circuit.

Finally it is concluded that due to the very rapid deaeration of the water there is a limited range of gas content within

which tests on cavitation may be realised. A suggestion is made that in order to enlarge the range of gas content, the water of the circuit should be saturated with some more soluble gas than atmospheric air. Carbon dioxide would be a suitable gas.

6. THE CAVITATION CIRCUIT:

6.1. Description of the cavitation circuit:

6.1.1. General:

The small cavitation circuit used for the experiments on the inception of cavitation in a small centrifugal pump was kindly lent to the University by the Fluids Division of M.E.R.L., East Kilbride. The same rig has been used first by Williams (Ref. 18) and later by Pearsall (Ref. 19) for their tests on the inception of cavitation on a small 2-dimensional diffuser with a divertor placed in the centre of the stream.

Basically, the rig consisted of two vertical cylindrical tanks of 18" diameter and 6 ft. height each. The two tanks were connected by two conduits. The lower conduit, of 1" bore, included the circulating pump while the higher conduit, of 2" bore, included the working section (FIG.1). The rig had an average capacity of water of 17 cu.ft.

In the new arrangement for the tests on the pump the same circuit was used with small alterations. The working section (diffuser) was replaced by a straight copper tube of 2" bore and the centrifugal pump which in the previous works had been used as the circulating pump was used as the test pump. The pump was

placed closed to tank I (FIG. 2). In the discharge side of the pump a venturi meter was placed for measuring the rate of flow through the pump. The rate of flow was controlled by a special type of valve Firth & Young (Ref. 34) which has freedom from cavitation over a wide range of working conditions and dissipates most of the energy supplied to the pump by friction at its solid boundaries. The characteristics of this valve are altered by varying the shape of these boundaries. Due to its freedom from cavitation this type of valve is often called non-cavitating valve (N.C.V.)

6.1.2. The test pump:

The centrifugal pump is a standard pump (No.22) manufactured by Messrs. Stuart-Turner Ltd. The details of the pump impeller are shown in FIG. 3 while that of the pump casing in FIG. 4. The pump is fitted with a D.C. motor of 0.95 HP. The speed of the pump is adjusted by rheostats connected in series with the motor. The cast iron casing of the pump was replaced by a similar one of perspex and the bronze cover of the impeller was also replaced by perspex in order to make the blades of impeller visible. The two approaches to the pump(suction and discharge tubes) were also made of perspex.

6.1.3. The Vacuum system:

Considerable time in preparing the circuit for the tests on cavitation inception in the pump was spent in obtaining a suitable arrangement for the vacuum system. The final arrangement, the methods employed and the precautions taken are briefly described below. The vacuum system is shown diagrammatically in FIG. 5.

The tops of the tanks I and II are connected through a water trap (T_1), a vacuum bottle (B) and a vacuum magnetic valve (M) to the vacuum pump. The type of vacuum pump used is an EDWARDS high vacuum pump model I.S 150 with an ultimate vacuum of 0.005 mm of mercury and 5.1 cu.ft/min. displacement.

The vacuum pump is also connected through another water trap (T_2) and a vacuum multi-switch (selector switch) (S) to the multitube manometer for removing the gases which might become trapped on the top of the pressure measuring tubes. To remove these gases easily the following arrangement and procedure has been adopted.

Referring to FIG. 5, during the normal operation of the vacuum system i.e. when we wish to raise the vacuum in the circuit, valve V_2 is closed and valve V_1 is open.

For removing the gases which have collected on the top of the manometer tubings, both V_1 and V_2 are closed for a few minutes while by introducing air into the circuit the pressure is raised to about atmospheric. Then with V_1 still closed V_2 is opened with the selector switch (S) in the OFF position. Due to the small capacity of the water trap (T_2) the vacuum is raised very quickly and by opening the switch suddenly to the positions 1 or 2 or 3, etc., a great difference in pressure is imposed locally to the corresponding tubing and the gases trapped are easily removed from the top of the manometer tubings.

Another problem which had to be solved was the detection and elimination of leakages of air into the circuit. Leakages of air affect both the dissolved and nucleic air content of the water in the circuit, and limit the ultimate vacuum of the system. At first

comparatively large leakages were discovered. An indication of the total rate of leakage of air into the circuit was found as follows. With the vacuum pump in operation the pressure in the system was reduced to a certain level. Then the vacuum pump was stopped. After that, readings of the level of mercury in one of the manometer tubes were taken at given intervals of time. The same procedure was repeated but this time, after the vacuum pump was stopped, the circuit was connected to the atmosphere through a given area (bore of a valve). New readings of the level of mercury in the same tube and for the same intervals of time were taken. The ratio of the change in level of mercury at a given interval of time was an indication of the total amount of leakage into the circuit. If the new change in level of mercury was not much larger than the corresponding first one that meant that serious leakages were taking place in the circuit.

After the detection and stoppage of the comparatively large leakages the circuit, having been emptied of water, was pressurized up to 15 p.s.i. and all the joints were spread one by one with a weak soap solution. The formation of soap film bubbles, was an indication of leakage and their rate of growth a measure of the magnitude of the leakage.* By this method minute leaks were detected. The best way to eliminate these minute leakages was found to be by the use of a mixture of APIEZON SEALING COMPOUND "Q" (Edwards High Vacuum) with a small quantity of high vacuum grease which was spread and pressed against the surface at the position of each leak.

* This method is applicable only for minute leaks. For comparatively large leaks the growth of soap film bubbles is so rapid that the bubbles break as soon as they start forming and it is not possible to see them.

With the methods described above almost all the leakages were detected and stopped. However, it was observed that when the pressure in the circuit was low a cloud of minute air bubbles could be seen travelling with the flow of water in the discharge branch of the pump without any sign of cavitation in the pump. This was more apparent for lower speeds of the pump. Apparently it was due to leakage of air into the pump casing through the gland of the pump spindle. This leakage was extremely undesirable where tests on inception of cavitation were to be made.

To stop this leakage the following simple device was invented.

The motor-pump unit had, between motor and pump casing, a ring of U cross-section used to support the pump casing on the motor body (FIG. 6). This ring in its cylindrical part had some holes to make the construction lighter. These holes were closed and a tapping was provided on the upper part of the ring to connect the space between motor and pump casing (S) to the top of tank I. By this arrangement the pressure (p_o) in space (S) was always equal to that in the top of the tank instead of being equal to atmospheric pressure as before. The pressure inside the casing of the pump is always greater than that in the top of the tank. Therefore it is not possible under any condition of operation for leakage of air to take place into the pump casing through the gland of the pump spindle. If the space S is disconnected from tank I (by tightening a clip on the ploythene tubing connecting the two spaces) after a few seconds a cloud of tiny bubbles appears, travelling with the current of water along the discharge branch of the pump. If the connection is re-made no bubbles appear.

However, although by the above device leakages of air into the

pump casing were eliminated, quite a large leakage took place through the bearing into space S, and this affected the value of the maximum attainable vacuum in the circuit. To eliminate this leakage the old ball-bearing was replaced by a new type (RANSOME & MARLES).

At first this could bear a vacuum as high as 27" of mercury but after a few days of operation its rubber ring failed and the vacuum started dropping. Finally a leather ring was fixed slightly tightly on to the shaft which was able to keep vacua as high as 27" of mercury during the period of the whole series of tests. Even with the provision of the leather ring, if space S were disconnected from tank I bubbles appeared in the discharge tube.

When increase in pressure was necessary, atmospheric air was let into the circuit via the tops of the tanks.

6.1.4. Pressure measurements by Manometer:

Pressure tappings were provided in various points in the circuit. All the mercury manometer columns have been mounted on a wooden board having a background graduated in tenths of an inch. The connections between the pressure tappings and the manometer columns are made with polythene tubing through T glass pieces. The third leg of each of the T pieces is connected to one position of the vacuum multi switch S. FIG. 5. The system of pressure tappings and manometer are shown in FIG. 7.

6.1.5. Adjustment of the total gas content.

a. Reduction of gas content - Deaeration.

Quick deaeration of the water takes place when a high vacuum has been created and the pump is set to operate at high speed.

Then violent cavitation appears in the pump and the gas content can drop from 100 to 20 - 25% of that of water saturated under atmospheric conditions in about half an hour. For finer adjustments both the vacuum and the speed of the pump should be reduced.

b. Increase of gas content - Aeration:

With a slight vacuum on the tops of the tanks the pump could be set to operate at high speed. Under these conditions a small amount of air would be continuously sucked into the circuit when a small tapping attached to the suction tube of the pump was opened to the atmosphere. The gas content would then increase and after 90 minutes the water would have a gas content greater than that corresponding to saturation under atmospheric conditions.

Although the gas content could be adjusted by the above methods to have any value between 20% and 100% of that of water saturated under atmopsheric conditions, the pressure in the circuit could not be controlled independently of the gas content. This resulted in some limitations in the range of variation of gas content depending on the particular test.

6.1.6. Measurements of total gas content:

The method of sampling used was the "Method A" described in detail in APPENDIX IV.

Measurements of total gas content were made by the gas content apparatus designed by the author (APPENDIX II) and the amounts of gases referred to N.T.P. were calculated by the method used by Kanellopoulos (Refs. 25 and 30). (APPENDICES II and III).

6.1.7. Control of the rate of flow:

For a given pump speed the rate of flow was controlled by adjusting the "travel" of the non-cavitating valve. This valve

provides quick and fine adjustment.

6.1.8. Speed of the pump:

The speed of the pump was controlled by adjusting the rheostats in series with the D.C. motor. The speed was measured by means of a stroboscope.

6.1.9. Temperature measurements:

The temperature of the sampling water was measured every time before the gas content measurements. From this the vapour pressure of the water for every individual test was determined.

6.1.10. Barometric Pressure:

A record of the barometric pressure was kept throughout the period of the inception of cavitation tests for the correction of the experimental results.

6.2. Calibrations made in the cavitation Circuit:

6.2.1. Calibration of the Venturi meter:

The method employed for the calibration of the venturi is described in APPENDIX VI.

The experimental results have been plotted as rate of flow against the difference in mercury level of the manometer columns connected to the venturi pressure tappings. The calibration equation derived from the experimental results by application of the method of least squares is also included in the APPENDIX.

The validity of the calibration of a venturi meter is limited. The limiting factor is the cavitation in the throat. As shown in the end of this APPENDIX the venturi is cavitation-free under all conditions in the circuit.

6.2.2. Calibration of the Motor:

For calibration of the motor a spring balance dynamometer was

used (APPENDIX VII) .

The experimental results for a number of motor speeds have been plotted as the motor brake horsepower (BHP) against ammeter indication. Due to possible changes of the mains voltage (232 - 250 Volts) the calibration was carried out by keeping the voltage across the motor constantly at 230 volts by means of a resistor. The calibration curves are very close straight lines and the corresponding equations were determined by application of the method of least squares.

6.2.3. Performance characteristics of the centrifugal pump:

The performance characteristics of the pump have been plotted for a number of speeds and these are discussed in APPENDIX VIII.

The Reynolds number effect on the head-capacity and efficiency-capacity characteristics are also discussed briefly in the same APPENDIX.

The present pump has a shape number (Addison) of 0.047 and its specific speed is

$$710 \quad \frac{(\text{gal})^{1/2}}{(\text{min})^{3/2}\,(\text{ft})^{3/4}}$$

The friction losses in the circuit were originally very large and the maximum rate of flow which the pump could generate was slightly larger than that corresponding to the best efficiency point at the nominal speed of 2850 rev./min. For further increase in the rate of flow the travel of the N.C.V. was increased a little.

6.2.4. Calibration of the manometers:

The system of the manometer tubes is shown schematically in FIG. 7.

Because the bore of the U glass tubes of the manometer are

never absolutely the same a given increase in the height of mercury in one leg of the U-tube is not associated with an equal decrease of that level in the other leg. Thus a calibration of the various tubes was undertaken.

This calibration served for checking the readings of the manometer. These readings have to be taken very quickly when tests on the inception of cavitation are carried out and consequently a false reading was probably registered when reading the manometer. On the other hand small pressure fluctuations possibly occurred even in the short interval of time for observing and recording the readings of the manometer in two adjacent tubes. Thus the above calibration curves were used for taking the mean of small pressure fluctuations.

7. TEST PROCEDURE:

7.1. Methods for defining the inception of cavitation:

The most popular methods for defining the inception of cavitation are two: the visual method, by the observation of small bubbles, and the audible method by listening for the formation and collapse of tiny bubbles in the zone of minimum pressure. The indicated inception condition may well depend on the optical or acoustical resolution possible although for most practical purposes, this is not important; Daily (Ref. 10), Crump (Ref. 15), Robertson et al (Ref. 35). The visual method is simple,and the detection of inception may be observed with the naked eye, and under ordinary lighting, when the cavitation is taking place in

stationary boundaries (e.g. venturi test section) or under stroposcopic light when studying the inception in rotating boundaries (e.g. blades of pump impeller). The acoustical methods may vary from the use of the human ear for pickup of the characteristic sound associated with the inception of cavitation, to the use of very sensitive hydrophones; Williams (Ref. 18), Pearsall (Ref. 19); Ross (Ref. 36). When the flow passes from that without cavitation to that with cavitation, the hydrophone output increases suddenly. As the intensity of cavitation increases further, the hydrophone output gradually levels off, continuing to climb at an ever decreasing rate. The sudden increase in the hydrophone output corresponds fairly closely to the visual inception of cavitation; Pearsall (Ref. 19).

The hydrophone method gives quite satisfactory results when cavitation is studied round a stationary boundary and the background noise is comparatively small. However in preliminary tests on the inception of cavitation in the blades of the impeller of the small centrifugal pump the author found no appreciable change in the hydrophone output from the flow without cavitation to that of intense cavitation. This was evidently due to the high level of background noise because the pump was connected straight on to the motor body. On the other hand due to the peculiar shape of the "volute" of the pump, cavitation in the "discharge nozzle" of the pump always commenced before the blades started cavitating (FIG. 7.1,1). The noise emitted from this region, which due to the small size of the pump was very near to the blades of the impeller, was interfering with the hydrophone output.

The optical method was adopted for determining the inception

of cavitation in the present tests.

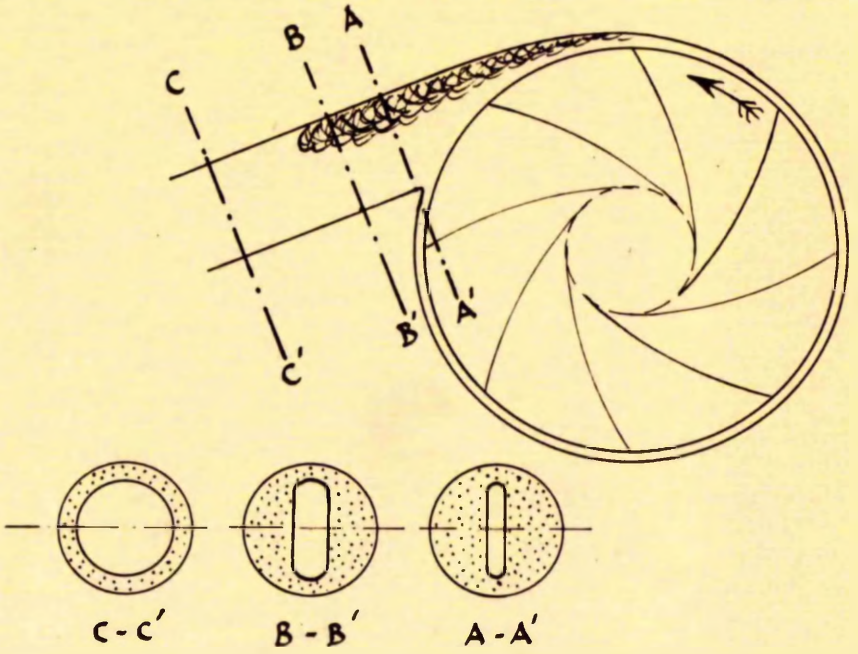


Fig. 7.1,1. Cavitation in the discharge nozzle of the pump.

As well as the above methods other ways have been used by various investigators for determining the inception of cavitation conditions. Ziegler (Ref. 17) in his test on the inception in a venturi test section determined the inception optically, acoustically and by means of a highly sensitive electrical vibration measuring device. Ter-Akopov (Ref. 37) devised a new instrument for detecting cavitation in a water turbine. The basis of this instrument is the measurement of a stream of light passed through the draft tube. In the instrument there is a photocell which remotely determines the amount and boundary of cavitation. His tests show that this instrument makes it possible accurately to determine the onset and degree of cavitation. Shmuglyakov (Ref. 23), in his experiments on the influence of dissolved gas content on the inception of cavitation in hydraulic turbines

determined the inception conditions as those under which an abrupt change in the cavitation characteristics of the turbine took place.*

The determination of inception based on the cavitation characteristics of a turbomachine does not coincide with the physical definition of the inception and it refers to a more fully developed stage of cavitation affecting the performance adversely. The change in performance may be abrupt or gradual, depending on the machine's specific speed, and a further definition often used is that critical condition where a one per cent. drop occurs in the efficiency-unit power curve; Winternitz (Ref. 1.)

7.2. Inception - Cessation of Cavitation:

Many investigators have noted a pronounced hysteresis in the critical pressures for cavitation. The critical pressure is much lower when approached from the non-cavitating state (inception of cavitation) than when approached from fully developed cavitation (cessation of cavitation); Crump (Ref. 15), Williams (Ref. 28), Kermeen et al (Ref. 38).

This hysteresis phenomenon was found to be more pronounced for low gas contents. The hysteresis appearing with inception is unstable and by making a small disturbance in the circuit the critical pressure for inception may be brought up to the level of critical cessation pressures. Due to this instability the scatter of results in tests for the determination of critical pressures for cavitation is larger when referred to inception than to cessation.

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* The cavitation characteristics of a turbine are defined by the relation $\eta = f(\sigma)$ where η is the efficiency and σ is the cavitation parameter.

A possible explanation for the observed hysteresis effects may be given by considering the conditions of the gas nuclei content of the water. For low gas content the equilibrium size of gas nuclei is small and thus when approaching cavitation from the non-cavitating state, low critical pressures should be expected. On the other hand when critical conditions are approached from the fully developed state of cavitation, gas bubbles of comparatively large size, remaining after the collapse of the cavitation cavities and travelling with the stream, may be, on entering the region of minimum pressure, the source of the continuing cavitation whose intensity gradually decreases. Thus the cessation pressure should be expected to be higher than the corresponding inception pressure.

As mentioned above this hysteresis effect is an unstable phenomenon and its magnitude may greatly depend on the geometry of the circuit as well as on the hydrodynamics of the flow and the dissolved and undissolved gas in the liquid medium. For example, hysteresis should not be expected in cases where cavitation may take place in another region in the circuit before it is going to start in the test section. This example has been confirmed by the author when studying the inception and cessation of cavitation in the blades of the impeller of the test pump. In this case (FIG. 7.1,1) cavitation always took place in the "discharge nozzle" of pump before the blades started cavitating. No noticeable difference in the critical pressures between inception and cessation of cavitation was observed in this case at the blade.

7.3. Description of the test procedure:

The critical conditions for cavitation in the blades of the small centrifugal pump were studied for various total gas contents

of the water and for various speeds of the centrifugal pump. The term critical conditions for cavitation in the present work is referred to the cessation of cavitation in the blades of the impeller determined by visual observation of the disappearance of the cavitation cavities under stroboscopic light. For obtaining as repeatable conditions as possible the cessation of cavitation was always observed in the passage between two arbitrarily chosen adjacent blades. This passage was painted black. The painting served two purposes; firstly it was used to mark the chosen passage and secondly the black paint gave a better background for observing the cavities.

The same batch of tap water was used throughout the tests on the inception. Immediately after filling the circuit with water another quantity of tap water was collected in a covered, comparatively large reservoir. This reservoir was used to provide water in the circuit for the loss of samples of water subtracted for gas content measurements.

The pressure in the gaseous space of the tanks could be changed from 2" of mercury absolute pressure up to atmospheric. Once the maximum vacuum had been created it could be kept without any noticeable drop for about half an hour after the circuit was disconnected from the vacuum pump.

As mentioned in Chapter 5, the deaeration of the circuit was found to be very rapid. The rate of deaeration increases as the pressure decreases. To avoid unnecessary and undesirably quick deaeration, a preliminary test was carried out to determine relative values of vacuum for the cessation of cavitation as a function of the speed of the pump, for the lowest value of gas

content of the water.

The test procedure kept throughout the experiments was as follows:

At the beginning of each run of tests the water in the circuit was slightly supersaturated under atmospheric pressure. With the centrifugal pump stopped, the vacuum pump was put in operation. When the vacuum in the system was raised to a given level (depending on the speed at which the run of tests was going to take place) the centrifugal pump was set to operate at about 2000 rev./min for the time necessary for taking a sample of water (APPENDIX IV). The temperature of the sample water was measured and recorded. After that the speed of the pump was set to its desired value and the vacuum pump was disconnected from the circuit. Then air was allowed to enter gently into the circuit by adjusting a valve and the pressure into the circuit was slowly and steadily increased, while the speed of the pump was kept as constant as possible by means of the rheostats in series with the D.C. motor. At the same time the black painted passage was observed; its apparent position had been "fixed" on the upper vertical of the pump by suitable handling of the stroposcope. At the moment when the cavities disappeared the valve allowing air into the circuit was immediately closed, while the actual speed of the pump was at that moment indicated by the stroboscope reading. The readings of the manometer were then taken as quickly as possible. The time when the cessation of cavitation took place was recorded.

The pump was set to operate again at about 2000 rev./min and while a new sample of water was taken into the sampling apparatus the previous sample enclosed in the gas content

apparatus was subjected to spraying to measure its gas content. This was found necessary for saving time. Otherwise it would not have been possible to obtain results for high gas content of the water.

After measuring the gas content of the first sample and introducing the second sample into the gas content apparatus the same procedure was followed for the second test and so on. Every run of tests was carried out at a given constant speed of the pump. The operations made for raising the vacuum, adjusting the ciruuit to the desired conditions, sampling of water and measuring its gas content for each individual test, provided also for the desired variation in total gas content of water. The gas content was reduced continuously with successive tests. The deaeration was very quick in the first tests when the gas content was high. The rate of deaeration continuously decreased and after a few tests the water had to be subjected to violent cavitation for a period of time (ranging from 10 min. to 4 hours) for its gas content to change appreciably. However even after 10 hours of deaeration with violent cavitation the gas content of the water in the present circuit could not reach below 20% of that corresponding to water saturated under atmospheric conditions.

After a run of tests (for a given speed of the pump) had been completed the water was subjected to aeration until its gas content was slightly higher than that corresponding to water saturated under atmospheric conditions. The circuit was then ready for the subsequent run of tests.

During the period of experiments a record of the barometric pressure was kept every half hour.

The levels of water in the two tanks when under vacuum were not always at the same horizontal plane. For this reason the level of water in tank I (close to the pump) was recorded at the moment when the cessation of cavitation took place. Also from time to time the polythene tubing connecting the pressure tappings to the manometer columns were checked. If air had been collected in the top of some of these tubes the method described in 6.1.3. was applied for its removal.

8. EXPERIMENTAL RESULTS ON THE CESSATION OF CAVITATION IN THE PUMP

8.1. Parameters used and interpolations made for the presentation of the experimental results:

8.1.1. Physical variables and parameters used:

Following the previous procedure tests on the cessation of cavitation in the blades of the centrifugal pump were carried out with the N.C.V. (flow regulating valve) fully open and for pump speeds 2000, 2200, 2450, 2650 and 2850 rev./min. The same tests were repeated for 2450 and 2850 rev./min with the N.C.V. adjusted to allow about $\frac{3}{4}$ of the maximum rate of flow.

The following physical variables and parameters were used for the presentation of the experimental results:-

i) The gas content of the water, measured with the gas content apparatus Kanellopoulos (Ref. 25) and corrected according to the analysis of errors Kanellopoulos (Refs. 25 and 30),and given in the following diagrams as the amount of gases referred to N.T.P.

and released from a given quantity of water is expressed by

α . . of gas N.T.P. per litre of water,

ii) Reference pressure for the cessation of cavitation, taken as the pressure measured by the tapping in the suction approach to the pump. This pressure is measured in feet of water column and symbolised by

$H_{s,cr.}$ . . ft. of water

iii) The rate of flow through the circuit, measured by the venturi meter and expressed in cubic feet of water per second, symbolised by

Q . . $ft^3/sec.$

iv) The speed of the pump measured in rev./min by the stroposcope; symbolised by

R.P.M. ----- (rev./min)

v) The non-dimensional pressure coefficient, (Thomas cavitation parameter) also used for the presentation of the experimental results

$$\sigma_{cr} = \frac{H_{s,cr.} - H_v}{H_d} \quad . \quad . \quad (8.1.1)$$

where

$\sigma_{cr.}$ is the value of the cavitation parameter when cessation of cavitation takes place;

$H_{s,cr.}$ is the pressure in the tapping position in the suction approach as defined previously;

H_v is the vapour pressure of the water corresponding to the temperature of the experiments and expressed in ft. of water column;

and H_d is the effective head of the pump (ft. of water) defined by FIG (8.1,1) and relation (8.1,3)

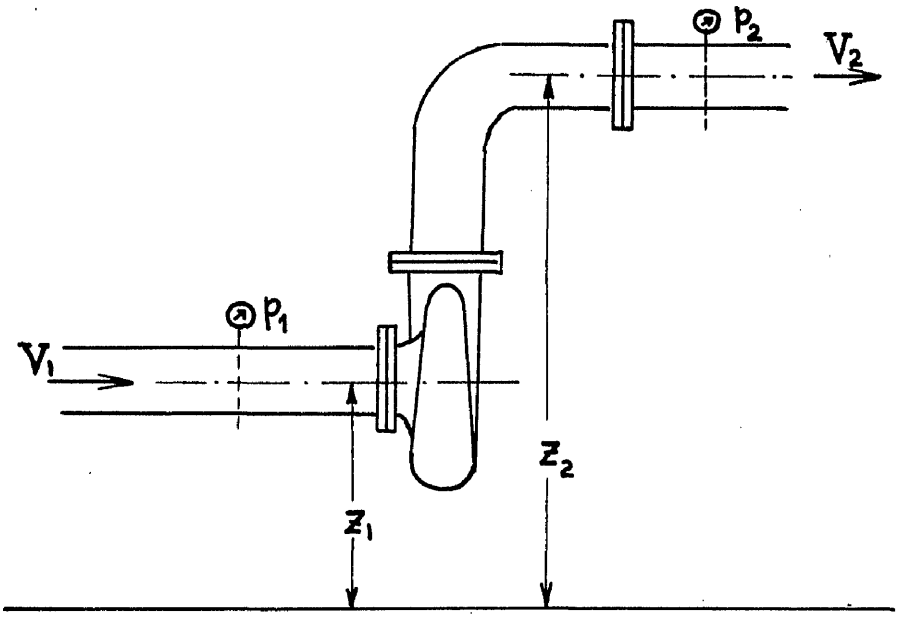


Fig. 8.1,1. Data for the determination of H_d.

$$H_d = \frac{p_2 - p_1}{\rho g} + \frac{V_2^2 - V_1^2}{2g} + Z_2 - Z_1 \quad \ldots (8.1.2)$$

where ρ is the density of water

g body force due to the gravity field

and $p_1, p_2, V_1, V_2, z_1, z_2$ as defined by FIG (8.1,1)

In the present circuit $A_1 = A_2$ and equation (8.1,2) becomes $V_1 > V_2$

$$H_d = \frac{p_2 - p_1}{\rho g} + Z_2 - Z_1 \quad \ldots (8.1.3)$$

vi) The Reynolds number, Kanellopoulos (Ref.39) page 83

$$R = \frac{VD}{\nu} \quad \ldots (8.1.4)$$

where

V is the tangential component of the absolute velocity of flow at the outer circumference of the impeller (ft/sec);

D is the outer diameter of the impeller in ft.;

and ν is the kinematic viscosity of the water taken in the present calculations as constant and equal to 10.8×10^{-6} ft^2/sec

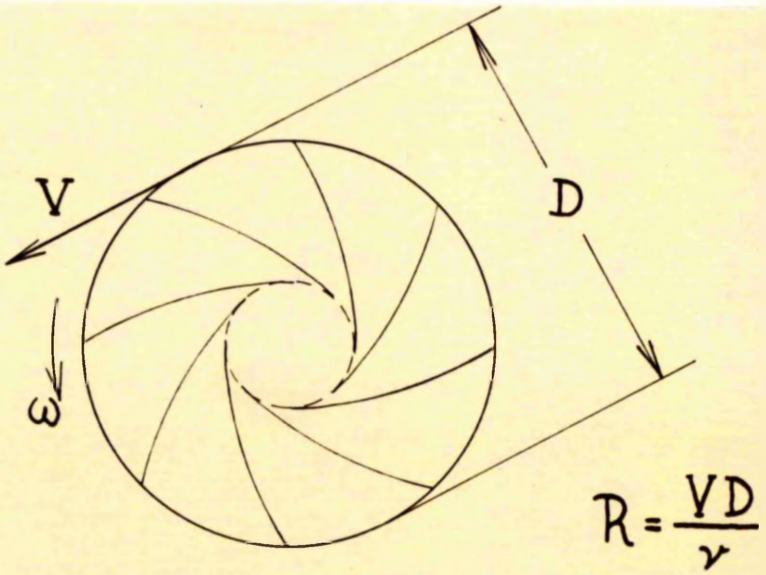
Substituting the value of V (FIG. 8.I.2) in (8.I.4) we obtain:

$$R = \frac{\pi}{60} D^2 \frac{RPM}{\nu} \quad \ldots\ldots \quad (8.I.5)$$

The diameter of the impeller is 4.4 inches,

and so $$D = 4.4" = \frac{4.4}{12} \text{ ft}$$

thus $$R = 650 \times (RPM) \ldots\ldots (8.I.6)$$



$$V = \omega \frac{D}{2} = \frac{2\pi (RPM)}{60} \cdot \frac{D}{2} = \frac{\pi}{60} (RPM) D$$

Fig. 8.1,2. Reynolds Number of a Pump.

vii) Finally, a non-dimenstional gas content parameter, introduced with the present tests and defined by the ratio

$$\frac{\alpha_s}{\alpha} ,$$

where

α is the total gas content of the water in the circuit as measured by the gas content apparatus;

and α_s is the gas content of the water saturated at a pressure equal to the reference pressure in the suction nozzle.

was calculated by the application of Henry's Law which yields

$$\frac{\alpha_s}{\alpha_o} = \frac{H_{s,cr}}{H_o} \quad \ldots \ldots (8.1.7)$$

where α_o is the gas content of water saturated under mean atmospheric pressure (H_o in ft. of water) and at a temperature of 20°C. α_o and H_o are constant and their values are approximately

$$\left.\begin{aligned} \alpha_o &= 22 \ \ cm^3/lt. \\ H_o &= 34 \ \ ft, \end{aligned}\right\} \quad \ldots (8.1.8)$$

therefore

$$\alpha_s = \alpha_o \frac{H_{s,cr.}}{H_o} = \frac{22}{34} H_{s,cr.} \ \ cm^3/lt.ft$$

and

$$\frac{\alpha_s}{\alpha} = 0.65 \frac{H_{s,cr}}{\alpha} \ \ cm^3/lt.ft \quad .. (8.1.9)$$

(where α must be expressed in cm^3/lt and $H_{s,cr}$ in ft.)

8.1.2. Interpolations made on the experimental results:

i) Reference pressure Hs

The reference pressure Hs was determined in two ways; firstly by measuring the pressure difference between (2) and (0) and secondly by calculating Hs by the relation

$$H_s = H_s' - \frac{V^2}{2g} - L_{1,2} \quad \ldots \ldots (8.1.10)$$

where

$$H_s' = H_o + \rho g h \quad \ldots \ldots (8.1.11)$$

and $L_{1,2}$ = losses from (1) to (2)

This was done to check for prerotation in the suction nozzle. No estimable difference between the observed and calculated values of Hs was found. That suggests that no appreciable prerotation takes place in the suction nozzle. To express Hs in units of absolute pressure a record of the barometric pressure was kept every half hour throughout the experiments.

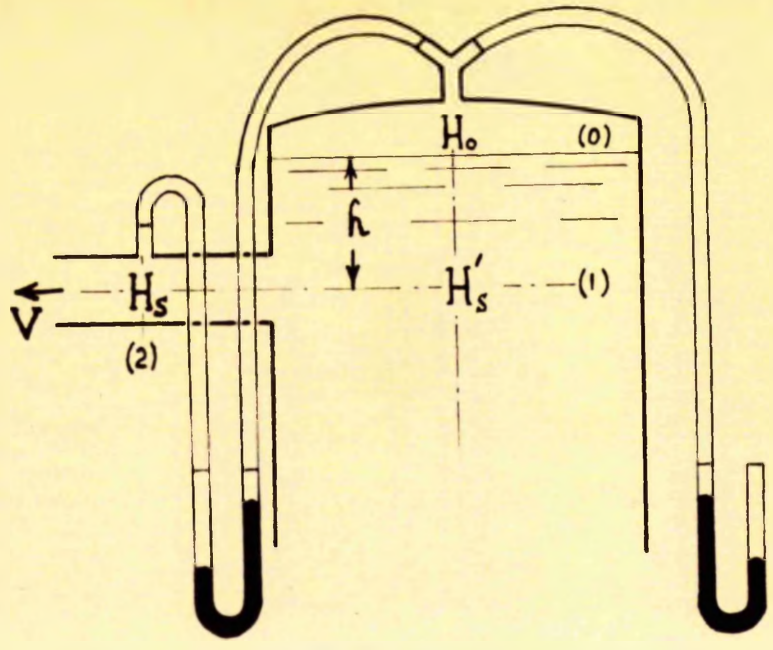


Fig. 8.1,3. Determination of H_s and H_s'.

ii) Speed of the pump:

It was not possible during the tests to keep the speed absolutely constant. To compensate for speed variations about the nominal value auxiliary graphs were plotted for the mean variation of reference pressure ($H_{s,cr}$) with R.P.M. for various values of gas content. From these graphs the results were reduced to the fixed-nominal - values of speed (2000, 2200, 2450, 2650, 2850 rev/min).

iii) Actual Gas content of water:

The gas content measured by the gas content apparatus could never coincide with the actual gas content of the water at the moment of cessation of cavitation. This is due to the time elapsing from the moment of the occurrence of cessation till the completion of the sampling process. During this period of time the deaeration of the water was continued and its rate depended on the magnitude of gas content. However by following always the same procedure described above and by keeping this period of

time as short as possible no large deviations between measured and actual gas content occurred. For more accurate determination of the actual gas content the variation of the measured gas content against time was plotted in graphs for each individual run of tests. It was then possible to draw the most probable curve through these points as representing the variation of the actual gas content with time. By keeping a record of the time at which the cessation took place in each test, the actual gas content could be determined quite accurately by means of these auxiliary graphs. Such a graph is shown in FIG.(8.1,4).

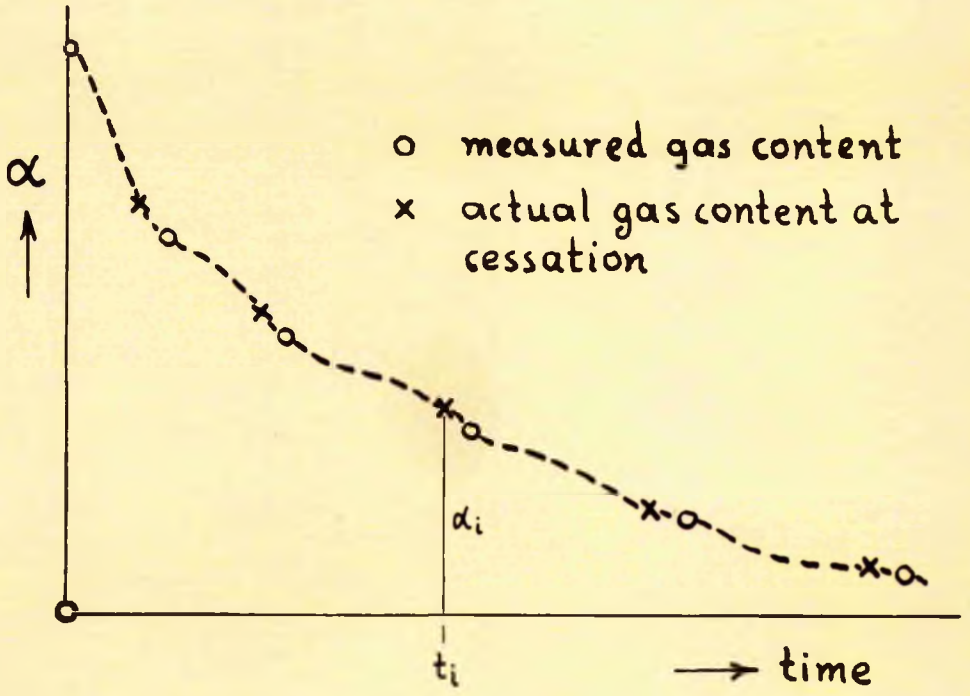


Fig 8.1,4. Determination of the actual values of gas content at cessation.

iv) For the calculations of σ_{cr} the values of vapour pressure should be known. The variation of vapour pressure (ft. of water column) with temperature (^{o}C.) is shown in FIG. 8. This figure has been plotted from the values of vapour pressure against

temperature given in the I.C.T. (Ref. 40).

8.2. Presentation and Interpretation of the Experimental Results on the Cessation of Cavitation in the Pump:

8.2.1., Variation of the critical reference pressure Hs_{cr} with the total gas content of water:

The variation of Hs_{cr} (ft. of water) with α $\left(cm^3/l\right)$, with the N.C.V. fully open, is shown in FIG. 9 for 2000, 2200, 2450, 2650 and 2850 rev./ min. of the centrifugal pump. In FIG 10 a similar diagram has been plotted with the N.C.V. opened to give about three-quarters of the maximum rate of flow for 2450 and 2850 rev./min.

In all these graphs in spite of the scatter of the results a definite influence of the total gas content on the cessation of cavitation conditions is evident. The higher the total gas content, the higher is the absolute static pressure at the suction tube of the pump for the persistence of cavitation in the blades of the impeller, i.e. the higher the total gas content, the greater is the danger of cavitation.

With the exception of the test run at 2450 rev./min, with the N.C.V. open to allow $\frac{3}{4}$ of the maximum rate of flow, in all the test runs the variation of Hs_{cr} against α is nearly a straight line over the range of total gas content tested. The slope of this line decreases as the speed of the pump increases. That is, the influence of total gas content on the critical conditions for cavitation is more pronounced in lower than in higher speeds of the pump. This is in accordance with the experimental results of Numachi's (Ref.14) work on the inception of cavitation in venturi shaped test sections.

A possible explanation for the above conclusion is given

below.

With the 'opening' of the N.C.V. kept constant the rate of flow through the circuit is proportional to the speed of rotation of the impeller of the pump. Thus the lower the speed of rotation the longer is the time which a given particle of water takes to travel through the various parts of the circuit.

On the other hand the pressure gradients in the various regions of the circuit are flatter for low than for high speeds of the pump.

Let us assume now that at a first approximation the critical cessation pressure, in the region where the conditions are more favourable for cavitation (region of minimum pressure), had the same magnitude for all the speeds of the pump at a given value of

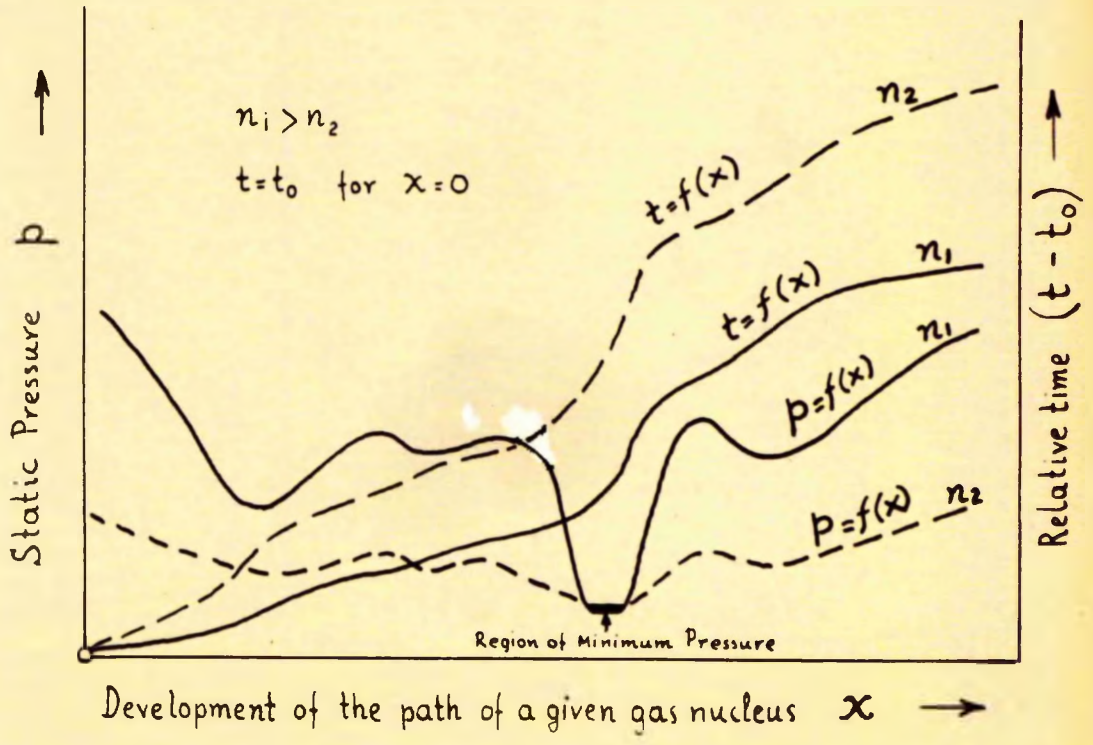


Fig 8.2,1. Static Pressure and Relative Time along the Path of a Gas Nucleus

the total gas content of water. Then the variation of pressure in the circuit will be smoother in lower than in higher speeds and in all the points of the circuit the level of static pressure will be lower for lower speeds than in the corresponding points for higher speeds. To illustrate better the above, the diagram shown in FIG.(8.2,1) has been plotted.

This figure shows roughtly the variation in static pressure along the path of a given gas nucleus for a high speed (n_1) and a low speed (n_2) . In the same figure the relative times taken by the gas nucleus to travel along its path is shown for the above two speeds. The rate of growth of the gas nucleus by diffusion is controlled by the total gas content of the water. This growth of the gas nucleus is increased the greater the relative times and the lower the static pressure along its path. Therefore, it is expected, according to the above explanation, that the influence of total gas content on the cessation of cavitation will be more pronounced for lower than for higher speeds.

The diagrams of the variation of $Hs_{,cr.}$ against α are very useful for illustrating the critical conditions of cavitation in a given pump. In these diagrams the critical conditions are expressed by the critical value of Hs which can be measured by a manometer connected to the suction approach to the pump. The variation of Hs can take place in two ways:-

(a) By varying the pressure on the top of the suction tank (as in the present experiments),

or (b) by varying the suction lift of the pump.

The relation between Hs and the suction lift (S) may be derived as follows:

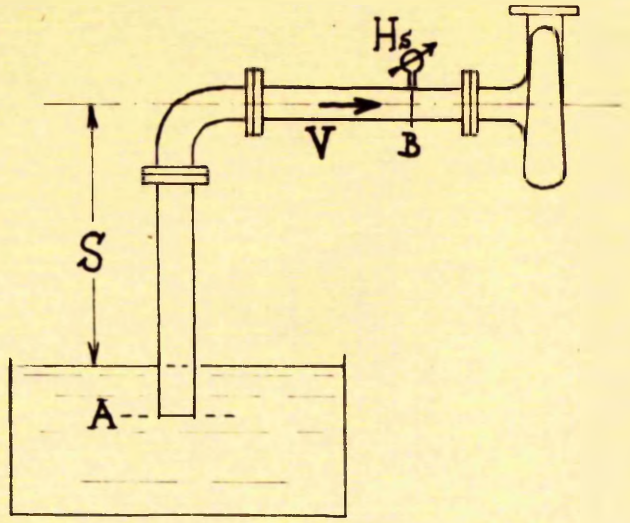


Fig. 8.2,2. Suction Lift (S).

Referring to FIG (8.2,2) we have

$$H_s + \frac{V^2}{2g} + S = H_{atm.} - L_A - L_{AB} \qquad (8.2.1)$$

where

$H_{atm.}$ is the atmospheric pressure in ft. of water,

L_A is the entrance loss at A " " " " ,

L_{AB} is the friction loss between section A and B in ft. of water,

and V is the velocity of flow through suction tube.

From (8.2,1)

$$S = H_{atm.} - H_s - \left(L_A + L_{AB} + \frac{V^2}{2g}\right) \qquad (8.2.2)$$

For a given length of suction tube L_{AB} is proportional to $\frac{V^2}{2g}$ while L_A is proportional to $\frac{V^2}{2g}$ and thus equation (8.2,2) becomes

$$S = H_{atm.} - H_s - K\frac{V^2}{2g} \; * \qquad (8.2.3)$$

For the critical conditions for cavitation

$$S_{cr.} = H_{atm.} - H_{s,cr} - K\frac{V^2}{2g} \qquad (8.2.4)$$

* K is not an absolute constant but depends on V. The actual variation of K with V may be found by calibration.

and for cavitation-free operation we must have

$$\sigma < \sigma_{cr} \quad \ldots \ldots \quad (8.25)$$

8.2.2. Variation of the critical cavitation parameter (σ_{cr}) with the total gas content of water:

The variation of σ_{cr} with α, with the N.C.V. fully open is shown in (FIG. 12) for 2000, 2200, 2450, 2650 and 2850 rev./min of the centrifugal pump. In (FIG. 11) a similar diagram has been plotted with the N.C.V. open to give about three quarters of the maximum rate of flow for 2450 and 2850 rev./min.

In spite of the scatter of the results the total gas content has evidently a definite influence on σ_{cr} at all the tested speeds. The influence of gas content on σ_{cr} is more pronounced in lower than in higher speeds, being very small for the test run at 2850 rev./min.

8.2.3. Variation of Hs,cr against speed of rotation for constant values of α

The variation of Hs,cr against speed of rotation (R.P.M.) is shown in FIG. 13 for α = 5, 10, 15 and 20 cm^3/lt with the N.C.V. at its fully opened position. In the same diagram Hs,cr has been plotted against rate of flow (Q), velocity of the water in the suction tube (V) and Reynolds number of the impeller (R).

The usefulness of such a diagram is that it provides a good illustration of how the critical pressure (h_{cr}) in the region of cavitation varies with both the total gas content and velocity of flow. For a given velocity of flow and speed of the pump, Hs,cr. is always increasing as α is increasing.

When approaching critical conditions for cavitation the

hydrodynamics of flow have not yet been disturbed appreciably and it is reasonable to assume that at a first approximation the pressure difference ($H_{s,cr} - h_{cr}$) is independent of the gas content of the water.

Thus for a given velocity of flow and speed of pump the above statement is expressed by the following relation

$$H_{s,cr} - h_{cr} = K = \text{constant} \quad . \quad . \quad . \quad . \quad (8.2.6)$$

where K is a function of pump speed.

Equation (8.2,6) is transformed into

$$h_{cr} = H_{s,cr} - K \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8.2.7)$$

Now if we accept that cavitation always starts at

$$h_{cr} \leq H_v \quad . \quad . \quad . \quad . \quad . \quad . \quad (8.2.8)$$

where H_v is the vapour pressure of the water, and that h_{cr} approaches H_v for the higher values of gas content, then

$$K = (H_{s,cr})_{max} - H_v \quad . \quad . \quad . \quad . \quad . \quad (8.2.9)$$

Substituting K from (8.2,9) into (8.2,7) we obtain

$$h_{cr} \leq H_{s,cr} - (H_{s,cr})_{max} + H_v \quad . \quad . \quad . \quad . \quad (8.2.10)$$

The interpretation of the last equation may be helped by the following examples:-

Example A. Pump operating at 2000 rev./ min with the N.C.V. fully open.

In this case

for α = 20 cm^3/lt $\qquad H_{s,cr} = (H_{s,cr})_{max}$ = I9 ft

for α = 5 " $\qquad H_{s,cr}$ = I3 ft

and

$$H_v = 0.7 \text{ ft}$$

Substituting the above values into equation (8.2,10) the

critical pressure at the region of cavitation with water having a gas content of 5 cm^3/lt is:

$$h_{cr} = 13 - 19 + 0.7 = -5.3 \text{ ft. of water.}$$

This means that for the low value of total gas content (5 cm^3/lt) a negative pressure(tension) of 5.3 ft. of water is necessary for cavitation conditions to become critical when the pump is running at 2000 rev./min.

Example B. Pump operating at 2850 rev./min with the N.C.V. fully open.

In this case

for $\alpha = 20\ cm^3/lt$ $\quad H_{s,cr} = (H_{s,cr})_{max} = 28.4$ ft

for $\alpha = 5$ " $\quad H_{s,cr} = 13$ ft

and $\quad H_v = 0.7$ ft

Thus for 5 cm^3/lt the critical pressure will be:

$$h_{cr} = 26.5 - 28.4 + 0.7 = -1.2 \text{ ft. of water.}$$

i.e. in this case again for 5 cm^3/lt a negative critical pressure is expected but its absolute magnitude is considerably smaller than that calculated in the previous example.

8.2.4. Variation of σ_{cr} with the speed of rotation for constant values of α

This variation is shown in (FIG. 14). In this figure σ_{cr} has been plotted against R.P.M., Q, V and R for α = 5, 10, 15 and 20 cm^3/lt and with the N.C.V. fully opened.

The curve corresponding to $\alpha = 20\ cm^3/lt$ shows that σ_{cr} at first slightly decreases as the speed of rotation increases up to about 2450 rev./min. As the speed increases further σ_{cr}

decreases at a higher rate.

The curve for $\alpha = 5$ cm^3/lt shows no appreciable change of σ_{cr} as the speed of rotation increases from 2000 to 2250 rev./min; beyond 2250 rev./min σ_{cr} increases with speed up to about 2650 rev./min and then starts decreasing as the speed increases beyong 2650 rev./min.

8.2.5. Variation of $H_{s,cr}$ with $\frac{\alpha_s}{\alpha}$ for the tested speeds of the pump.

The non-dimensional gas content parameter $\frac{\alpha_s}{\alpha}$ introduced into the present work has been defined previously in the text (8.1.1.vii). It expresses the degree of supersaturation or undersaturation of water having actual gas content α, with reference to the arbitrarily selected pressure Hs. The water is considered to be saturated with reference to Hs when $\alpha = \alpha_s$.

For $\frac{\alpha_s}{\alpha} > 1$ the water is undersaturated

while for $\frac{\alpha_s}{\alpha} < 1$ the water is supersaturated.

The variation of Hs,cr with $\frac{\alpha_s}{\alpha}$ is shown in FIG (15). It can be seen from this figure that there is a value of $\frac{\alpha_s}{\alpha}$ between 1.5 and 2.5, depending on the speed of the pump, which divides each curve in two parts. At any speed for values of $\frac{\alpha_s}{\alpha}$ higher than this "transition" value $\left(\frac{\alpha_s}{\alpha}\right)_t$, the critical reference pressure remains nearly constant, while for $\frac{\alpha_s}{\alpha} < \left(\frac{\alpha_s}{\alpha}\right)_t$ Hs,cr increases slowly at first with a rapidly increasing rate as $\frac{\alpha_s}{\alpha}$ decreases further, the rate of increasing Hs,cr being higher for lower speeds of the pump. The "transition" value of $\frac{\alpha_s}{\alpha}$ decreases as the speed of the pump decreases.

The variation of Hs,cr with $\frac{\alpha_s}{\alpha}$ should be associated with the growth of gas nuclei by diffusion of gases in solution.

If such is the case $\left(\frac{\alpha_s}{\alpha}\right)_t$ should be expected to be near unity.

A reasonable explanation for $\left(\frac{\alpha_s}{\alpha}\right)_t$ being in all cases much larger than unity is the fact that Hs,cr and therefore α_s are measured at an arbitrarily chosen point in the suction tube of the pump. Accordingly the positioning of the tapping for the new reference pressure $\left(H'_{s,cr}\right)$ should be somewhere downstream of the existing one where the $H'_{s,cr}$ would correspond to a new α'_s which would fulfil the relation

$$\left(\frac{\alpha'_s}{\alpha}\right)_t \simeq 1$$

8.3. The cavitation parameter:

Thoma's cavitation parameter defined by the relation

$$\sigma = \frac{H_s - H_v}{H_d} \quad * \quad \ldots\ldots \quad (8.3.1)$$

is a non-dimensional parameter and its purpose was to serve as a criterion of similarity in flows with cavitation.

According to its definition the critical conditions for cavitation in a hydraulic installation of given geometric characteristics should be reached for a constant value σ_{cr} of σ which may be determined from measurements of the "reference" pressure Hs. If Hs,cr is the critical value of the reference pressure then according to (8.3,1):

$$\sigma_{cr} = \frac{H_{s,cr} - H_v}{H_d} \quad \ldots \quad (8.3.2)$$

---

*This is the form of Thoma's cavitation parameter with application in pumps. For cavitation in stationary boundaries σ is expressed as

$$\sigma = \frac{p_\infty - p_v}{\rho V_\infty^2/2} \quad \ldots\ldots \quad (8.3.1a)$$

where p_∞ and V_∞ are respectively the static pressure and velocity at an arbitrary point of reference, p_v is the vapour pressure and ρ is the density of the water.

However, it has by now been proved by a great number of investigators that σ_{cr} is not only a simple function of the geometry of the installation. Even for the same test section in a given hydraulic circuit, σ_{cr} is found to depend on the hydrodynamics of flow and on the total gas content of the water.

In parallel experiments on the pressure at which cavitation commences it has been shown that there is not a fixed value for the critical pressure (h_{cr}). Studies on the mechanics of cavitation inception have shown theoretically and confirmed experimentally that

$$h_{cr} \leq H_v \quad . \quad . \quad . \quad . \quad (8.3.3)$$

and that h_{cr} depends on the size of the gas nuclei when entering the region where cavitation is going to take place. In turn the size of gas nuclei at this stage depends on the total gas content of the water and the rate of flow through the circuit. Accordingly a first improvement in the expression for the cavitation parameter would be to replace the term H_v by h_{cr} (relations 8.3,1 and 8.3,2).

Following the analysis in § 8.2.3 of the present work the effect of gas content on the inception of caviation may be included in the expression for the cavitation parameter.*

Equation (8.2,10) gives

$$h_{cr} = H_{s,cr} - (H_{s,cr})_{max} + H_v \quad . \quad (8.3.4)$$

---

*It must be emphasized from the beginning that the following analysis is based on the limited range of the present experimental work and on the assumption that the critical inception pressure approaches H_v with water of high gas contents.

From the experimental results shown in FIG. 9, the mean value of Hs seems to change linearly with the gas content and the slope of each of these lines depends on the speed of rotation of the impeller.

Let $\alpha_{max.}$ be the value of the gas content at which $h_{cr.}$ approaches the value of vapour pressure and ξ be the slope of the straight line representing the Hs,cr against α variation. Then

$$\frac{(H_{s,cr.})_{max.} - H_{s,cr}}{\alpha_{max.} - \alpha} = \xi \quad \ldots (8.3.5)$$

and

$$(H_{s,cr})_{max.} - H_{s,cr} = \xi(\alpha_{max.} - \alpha) = \frac{\xi}{\alpha_{max}}\left(1 - \frac{\alpha}{\alpha_{max}}\right) \quad (8.3.6)$$

Let $\frac{\xi}{\alpha_{max}}$ be ξ' and substitute the value of $(H_{s,cr})_{max} - H_{s,cr}$ into (8.3,4). Then: $h_{cr} = H_v - \xi'\left(1 - \frac{\alpha}{\alpha_{max}}\right)$ . . . (8.3,7)

The effect of gas content may be taken into consideration in the expression for the critical cavitation parameter if the term H_v in equation (8.3,2) is replaced by the value of h_{cr} given by (8.3,7). Then the expression for the new form of the cavitation parameter becomes

$$\sigma'_{cr.} = \frac{H_{s,cr} - \left\{H_v - \xi'\left(1 - \frac{\alpha}{\alpha_{max}}\right)\right\}}{H_d} \quad \ldots (8.3.8)$$

and the relation between σ_{cr} and σ'_{cr} is:

$$\sigma'_{cr.} = \sigma_{cr} + \frac{\xi'(1 - \alpha/\alpha_{max.})}{H_d} \quad \ldots (8.3.9)$$

where $\xi' \cong H_d$ and depends on the speed of rotation.

For a given constant value of the speed of rotation σ'_{cr} is independent of the total gas content of the water.

9. TESTS WITH VARIOUS DEGREES OF CAVITATION:

9.1. Variation of Q and Hd against Hs:

These tests were carried out with tap water of low total gas content $\left(5\ \frac{cm^3}{lt}\right)$, with the N.C.V. fully opened and for pump speeds of 2000, 2200, 2450, 2650 and 2850 rev./min.

The variation of Q against Hs is shown in FIG. 16 while the variation of Hd against Hs is shown in FIG. 17.

In both these graphs the dotted-line curves represent the cessation of cavitation in the blades of the impeller for the values of total gas content α = 5, 10, 15 and 20 $\frac{cm^3}{lt}$. The curves $\alpha = 5\ \frac{cm^3}{lt}$ and $\alpha = 20\ \frac{cm^3}{lt}$ divide the planes Q, Hs and Hd, Hs in three regions. The region on the right of the dotted-line curve $\alpha = 20\ \frac{cm^3}{lt}$ represents the conditions at which the impeller of the pump is free from cavitation independently of the gas content of the water. The region on the left of the $\alpha = 5\ \frac{cm^3}{lt}$ curve represents the conditions under which cavitation is always present in the impeller, while the region between the curves $\alpha = 5\ \frac{cm^3}{lt}$ and $20\ \frac{cm^3}{lt}$ is the region at which cavitation may or may not be present depending on the gas content of the water.

The somewhat peculiar change of Q and Hd with Hs for low values of Hs is due to the fact that cavitation appears also in other parts of the circuit besides appearing in the impeller. It was found that cavitation always appeared in the discharge nozzle of the pump casing before it set up in the passages between the blades of the impeller. On the other hand when the pump was operating at its higher tested speeds (2650 and 2850 rev./min) and when the static pressure in the circuit was low a large quasi-steady vapour bubble appeared in the part of the suction

tube connected to the suction tank. This bubble expanded as the static pressure was reduced further. The appearance and expansion of this bubble is mainly responsible for the sudden drop of the Q,Hs curve and the rising of the H_d, H_s curve at very low values of Hs and at the higher tested speeds of the pump.

9.2. The H_d, Q characteristics of the pump plotted against various values of total gas content and reference pressure Hs.

The results of these experiments are shown in FIG. 18, 19 and 20. Each of these graphs has been plotted for a constant value of gas content and for three speeds of the pump namely 2000, 2450 and 2850 rev./min. For each speed of the pump the H_d,Q characteristics have been plotted for three values of the reference suction pressure Hs, namely 6, 18 and 33 ft. of water abs. Each individual curve has been determined for 5 fixed positions of the N.C.V. which, starting from the fully opened position of the valve towards the shut position, have been symbolized by: NCV1, NCV2, NCV3, NCV4 and NCV5.

It should be mentioned from the beginning that during these tests the gas content α, reference pressure Hs and positions of the N.C.V. could not be kept absolutely constant at their desired value. However every possible care was taken to minimize such deviations. The values of gas contents, reference pressures and positions of the N.C.V. are therefore mean values and positions.

FIG. 18 shows the variation of the H_d,Q characteristics of the pump for water with a mean gas content of 5 cm^3/lt

FIG 19 includes similar curves to that of FIG. 18 with a mean gas content of 13 cm^3/lt.

FIG. 20 shows the variation of H_d, Q characteristics for water with a mean gas content of 18 cm^3/ft but only for H_s = 18 and 33 ft. of water. The corresponding curves for H_s = 6 ft. of water could not be obtained due to the very quick deaeration of the water in this case.

From the same experimental results the curves shown in FIGS. 21, 22 and 23 have been plotted. FIG. 21 contains all the experimental results under a mean reference pressure H_s = 33 ft. of water. FIG. 22 is a similar graph but for H_s = 18 ft. of water and FIG. 23 is for H_s = 6 ft. of water.

From FIGS. 18 to 20 it seems that independently of gas content the head of the pump is reduced as the reference suction pressure is reduced, this effect being more pronounced for higher speeds of the pump and for a given speed for greater rates of flow. This is quite clear in the case of low gas content ($\alpha = 5$ cm^3/ft) FIG. 18. But in the case of $\alpha = 13$ cm^3/ft and H_s = 6 ft. of water, the change in the H_d, Q characteristics is different from the trend of change shown by all the other curves. Whereas under all the other conditions the H_d, Q characteristics do not show any appreciable change in the pump head with static head at low rates of flow, the curves plotted for $\alpha = 13$ cm^3/ft and H_s = 6 ft. show much lower heads as the rate of flow is reduced. This may be due to the fact that all these graphs have been plotted under the assumption that the density of the operating liquid is constant throughout these tests. However for a comparatively high value of gas content and for very low reference suction pressures (6 ft. of water abs.) part of the dissolved gases comes out of solution and the actual "density" of the mixture of water and released gases is

less than the density of pure water. If the pump head could be expressed as the height of the column of the mixture of water and released gases then the actual head of the pump would be higher than that given by the curves for $\alpha = 13 \frac{cm^3}{et}$ and $H_s = 6$ ft. of water.

The tendency for the dissolved gases to come out of solution and therefore interfere with the density of the water may be represented by the values of the ratio $\frac{\alpha_s}{\alpha}$ (8.1.1,vii). For the tested values of gas content and reference suction pressure the following table can be formed for the corresponding values of $\frac{\alpha_s}{\alpha}$.

Values of $\frac{\alpha_s}{\alpha}$ for the tested values of α and H_s

α (cm^3/et) \ H_s (ft)	33	18	6
5	4.3	2.35	0.78
13	1.65	0.90	0.30
18	1.20	0.65	

The lower the value of $\frac{\alpha_s}{\alpha}$ the higher is the degree of supersaturation of the water with reference to the conditions at the arbitrarily selected reference suction pressure H_s and therefore the higher is the rate of release of gases from the solution.

The fact that, for instance, the H_d, Q curves plotted for

$\alpha = 18\ cm^3/lt$ and $H_s = 18$ ft. corresponding to a value of $\frac{\alpha_s}{\alpha} = 0.651$ do not show any appreciable change in the density of the water is not surprising; the choice of α_s as a reference gas content is entirely arbitrary and for the released gases to affect appreciably the density of the operating liquid-gas mixture a considerable amount of gases should come out of the solution. However comparing this value of $\frac{\alpha_s}{\alpha} = 0.65$ with that of $\frac{\alpha_s}{\alpha} = 0.30$ we see that the water passing the reference pressure tapping at the conditions $\alpha = 13\ cm^3/lt$ $H_s = 6$ ft., is more than twice supersaturated in comparison with the water passing the same point and at conditions $\alpha = 18\ cm^3/lt$ $H_s = 18$ ft.

From FIGS. 21 to 23, plotted to show the effect of gas content on the H_d, Q characteristics of the pump, it is evident that no definite conclusion may be drawn as to how the gas content affects the performance of the pump. Change in density of the operating liquid and the possibility of the appearance of cavitation at high gas contents and low static pressures in other parts of the circuit besides the blades of the impeller does not allow us to say that gas content affects the H_d, Q characteristics for small rates of flow as one could at first conclude from these figures. However it can be said that total gas content does not appreciably influence the head of the pump for high rates of flow.

Finally FIG. 24 contains a number of photographs of the impeller of the pump under various degrees of cavitation.

The photographic data is:-

$2\frac{1}{4}$" x $2\frac{1}{4}$" Agiflex III Camera. 80 cm f2.8 Agilux lens with extension tube (Stop used f 5.6.)

FILM: Ilford FP3 developed in Microdol for 14 mins.
Light Source: Ernest Turner speed flash HS/5 Siemens SE1 Xenon Tube, 20 Joules at 12 microseconds. Both camera and light were about 2 ft. away from pump.

10. CONCLUSIONS:

The influence of total gas content on both the incipient and developed stages of cavitation was studied in a small centrifugal pump. Throughout the tests the same batch of tap water was used. Adjustment of the total gas content to the desired value was made by aeration or deaeration. From the results of the present investigations we can conclude:

(1) The total gas content does influence the cessation of cavitation. In spite of the scatter of the experimental results a definite influence of the total gas content on the cessation conditions is evident. For a given speed of the pump and "opening" of the flow regulating valve the higher the total gas content the higher is the critical suction reference pressure ($H_{S,CY}$)

(2) With the exception of the test run at 2450 rev./min with the N.C.V. opened to allow $\frac{3}{4}$ of the maximum rate of flow, in all the test runs the mean variation of $H_{S,CY}$ against total gas content is linear.

(3) The effect of total gas content on the cessation is more pronounced in lower than in higher speeds. This is probably due to the fact that in lower speeds the time taken by a gas nucleus to travel through the lower pressure zone is longer than when the pump is operating at higher speeds. Thus, the increase of the size of the gas nucleus by diffusion is larger the lower the speed of the pump.

(4) The present experimental results are in qualitative agreement with the results of similar works of Smuglyakov, Numachi and Crump.

(5) The present experimental results when plotted as critical

suction reference pressures against the introduced non-dimensional gas content parameter α_s/α show that for each speed there is a "transition" value of the above ratio beyond which the mean value of $H_{s,cr}$ remains constant. For values of this ratio lower than the "transition" value the cessation pressure increases rapidly as α_s/α decreases. This effect is more pronounced at lower than at higher speeds. As explained in the text the manner in which $H_{s,cr}$ depends on α_s/α verifies the assumption that cavitation originates on gas nuclei the growth of which may be helped by diffusion of the dissolved gases into the nuclei as the latter pass through the low pressure region where the water may be supersaturated.

(6) Cavitation begins with the growth of gas nuclei stabilized in the liquid. The equilibrium size and growth of these nuclei is intimately connected with the total gas content of the liquid. The scatter of the results may be explained by the statistical distribution of the equilibrium size of the gas nuclei.

(7) Calculations based on the reasonable assumptions (a) that the critical cessation pressure never exceeds the vapour pressure of the water, approaching this value for high gas content, and (b) that at conditions near to cessation the hydrodynamics of flow have not been disturbed, show that with the pump running at 2000 rev./min. and with water of 5 cm^3/lt total gas content a negative pressure of 5.3 ft of water should be expected to be the limit for cavitation-free operation of the pump. Under the same conditions but at 2850 rev./min. a negative pressure of only 1.2 ft of water should be the corresponding limit.

(8) Based on the same assumptions, as above, and in the light of the present experimental results, the expression for the critical

value of Thoma's cavitation parameter may be corrected by the addition of a term which includes the total gas content effect on the cessation of cavitation.

(9) From the experiments on various degrees of caviation no decisive conclusions may be drawn on the effect of total gas content on the performance characteristics of the pump for small rates of flow (small "openings" of the N.C.V.). Nevertheless it can be said that total gas content does not appreciably influence the head of the pump for high rates of flow.

(10) Due to the rapid deaeration of the water the highest value of total gas content at which tests on cavitation may be realised is limited (about 20 cm^3/lt). In order to increase the range of total gas content the water of the circuit should be saturated with a more soluble gas than atmospheric air (e.g. carbon dioxide).

(11) A great help to investigators dealing with total gas content effects would be the development of a reliable automatically recording gas content meter operating with a short time-lag.

Such an apparatus could be developed either by the automation of one of the extraction methods (e.g. M.E.R.L, Kanellopoulos), or by suitable application of the thermal conductivity method.

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LIST OF FIGURES*

*Figs. 3.1 to 8.2,2 appear in the text. FIGS 1 to 24 have been placed at the end of the thesis before the APPENDICES.

FIG. 14. Variation of σ_{cv} with R.P.M., Q, V, and R.

FIG. 15. Variation of $H_{s,cr}$ with α_s/α .

FIG. 16. Variation of Q with H_s

FIG. 17. Variation of H_d with H_s

FIG. 18. Variation of H_d with Q. α = $5^{cm^3}/_{lt}$

FIG. 19. Variation of H_d with Q. α =13 "

FIG. 20. Variation of H_d with Q. α =18 "

FIG. 21. Variation of H_d with Q. H_s =33 ft.

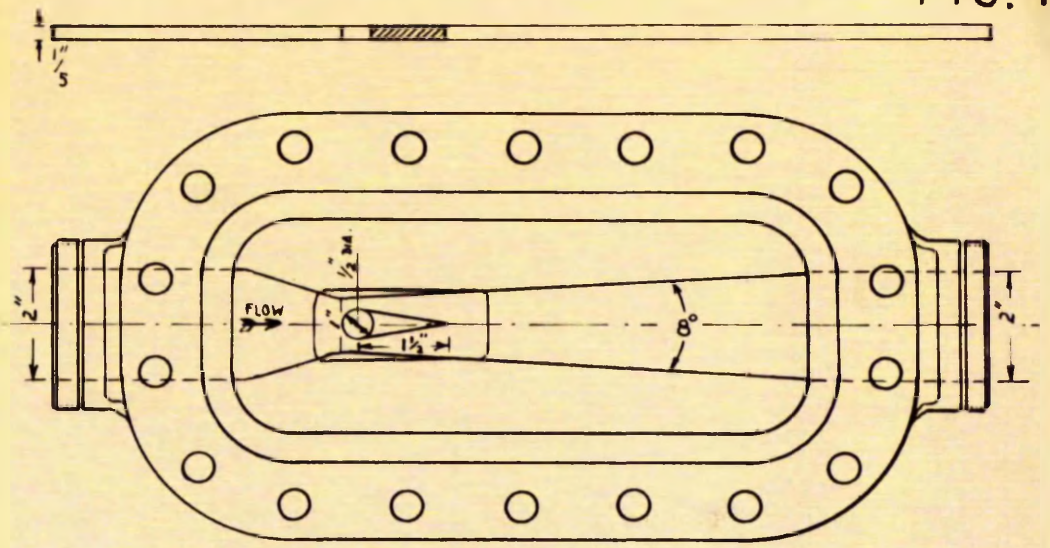
FIG. 22. Variation of H_d with Q. H_s =18 ft.

FIG. 23. Variation of H_d with Q. H_s = 6 "

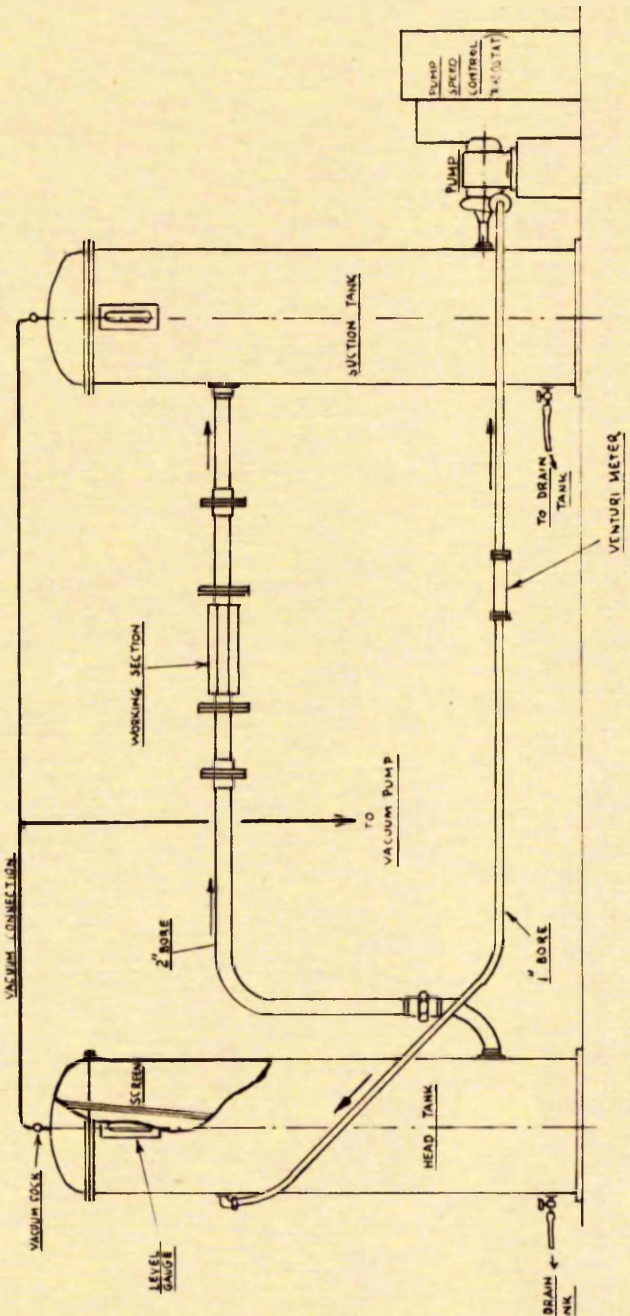
FIG. 24. Photographs of the impeller.

LIST OF APPENDICES

FIG. 1.



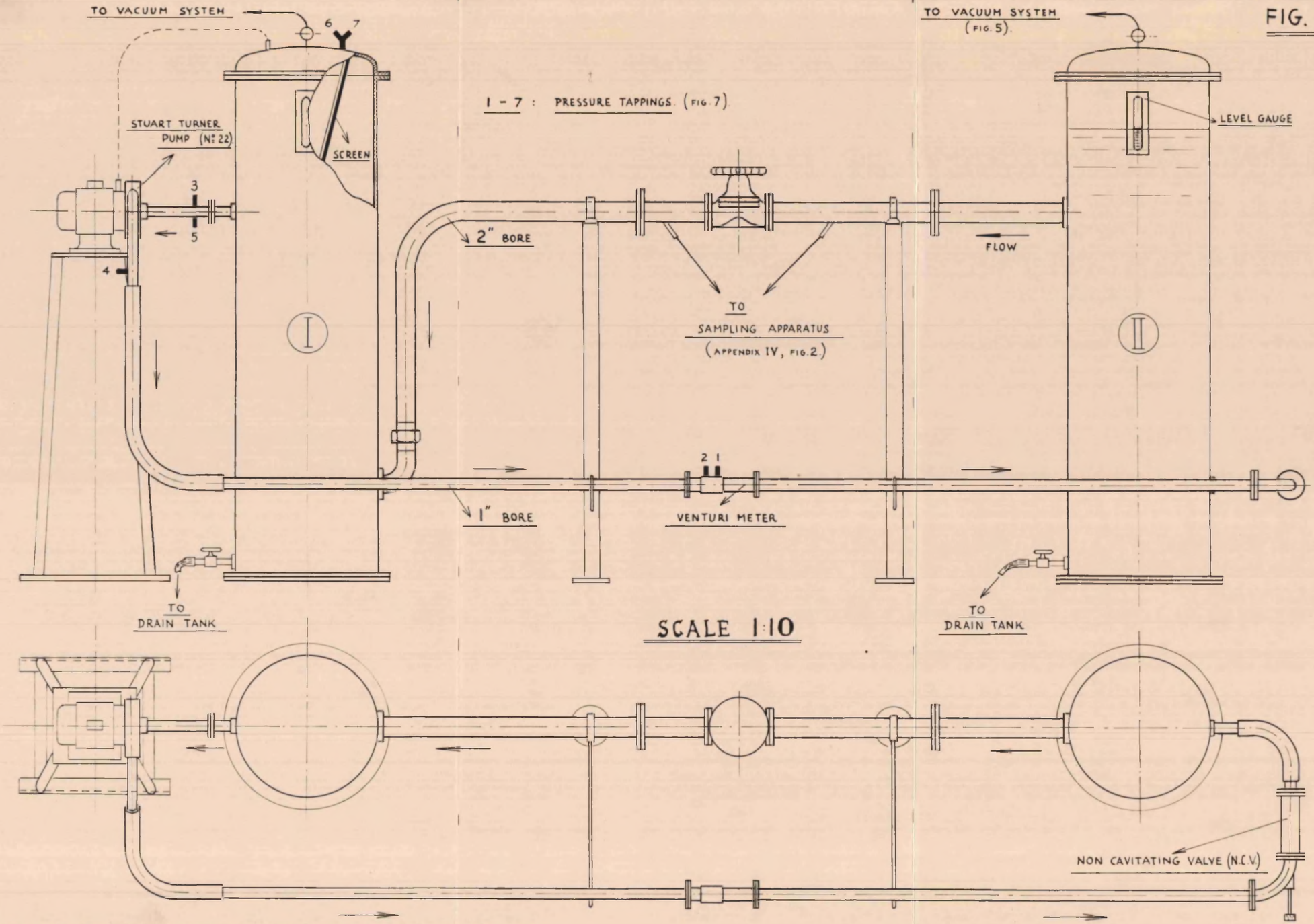
WORKING SECTION.



CAVITATION RIG.

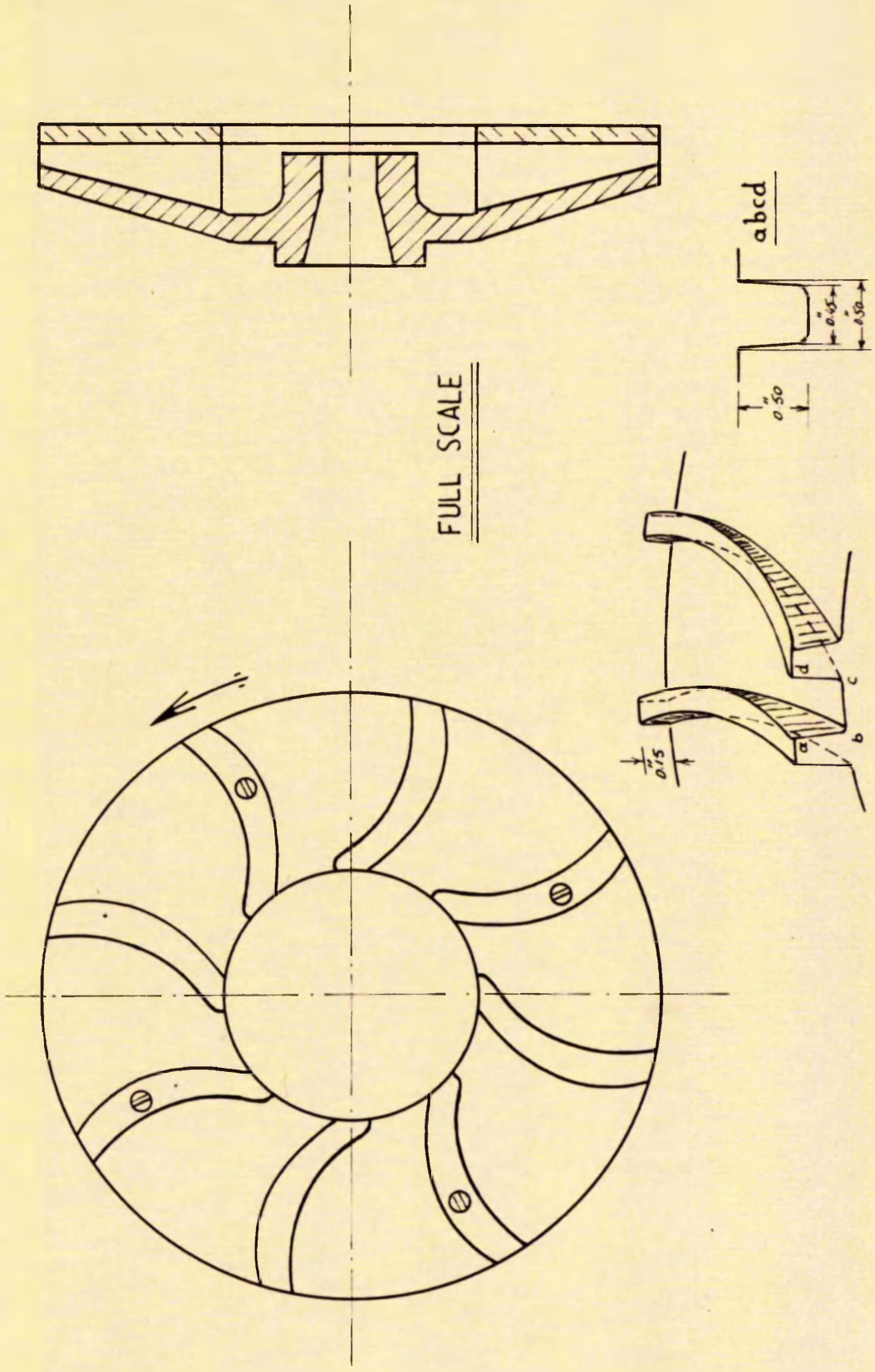
Cavitation Rig used by Williams (MERL).

FIG. 2



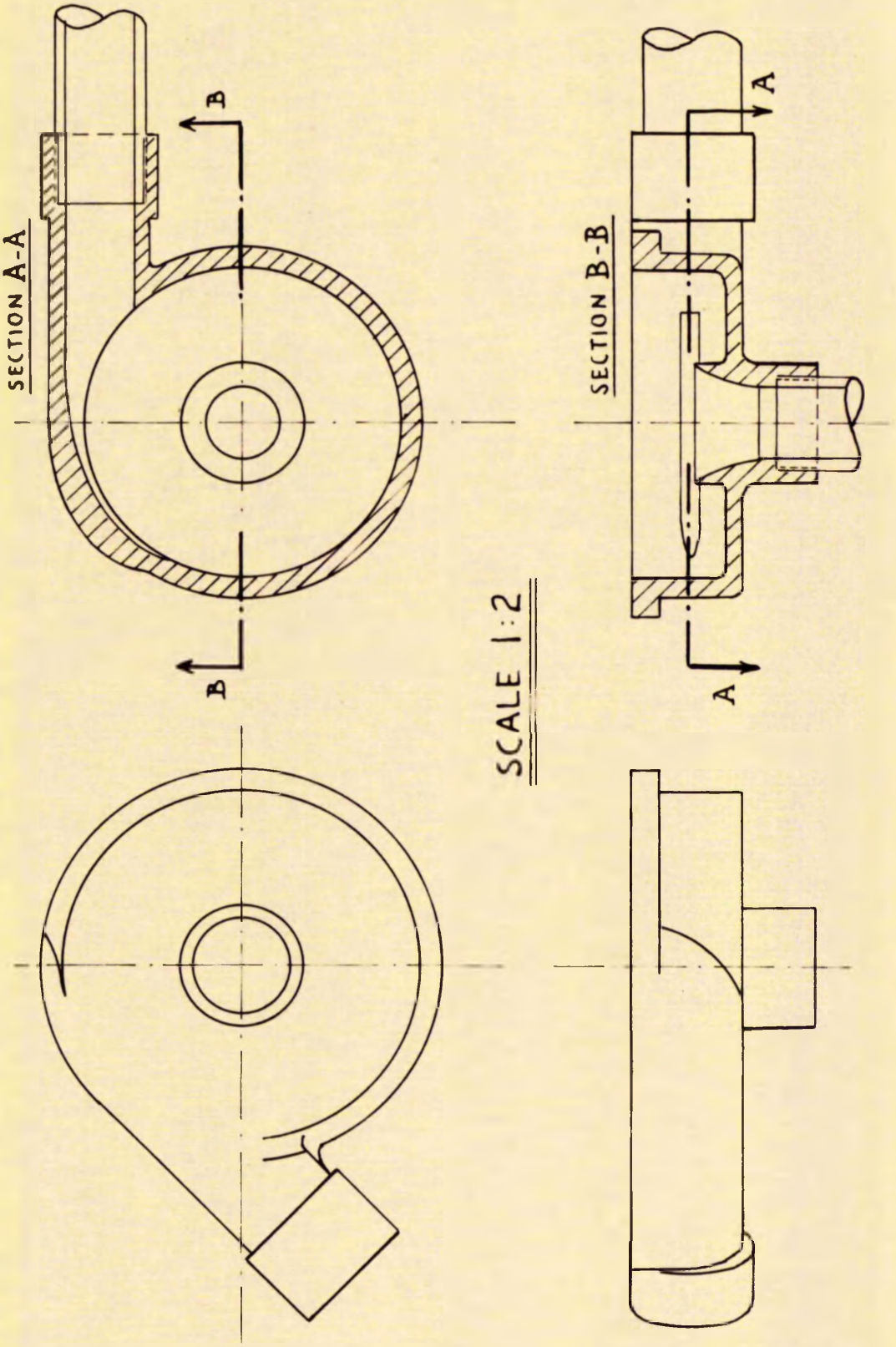
CAVITATION RIG USED IN THE PRESENT TESTS.

FIG. 3.



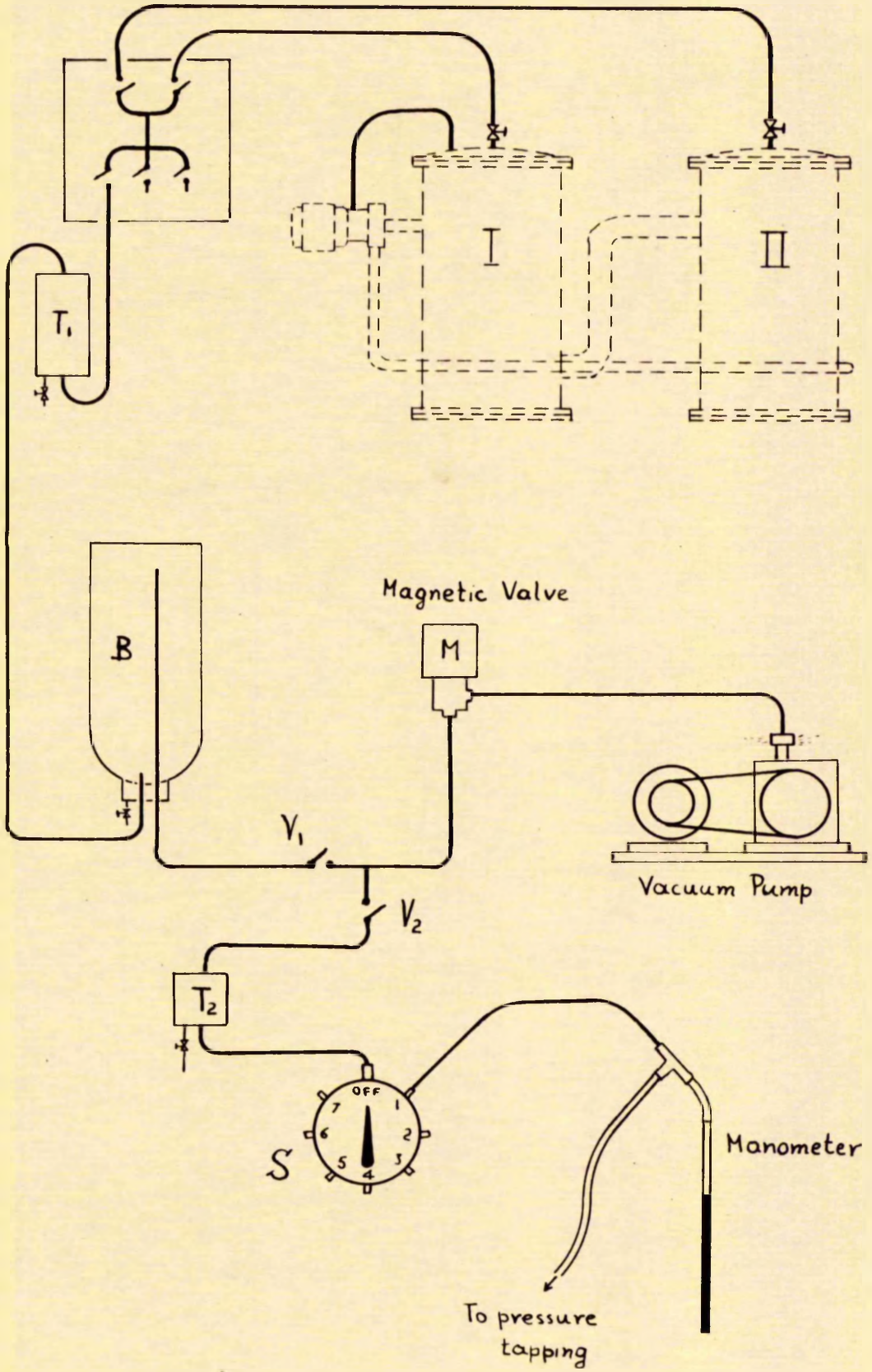
Pump Impeller.

FIG. 4.



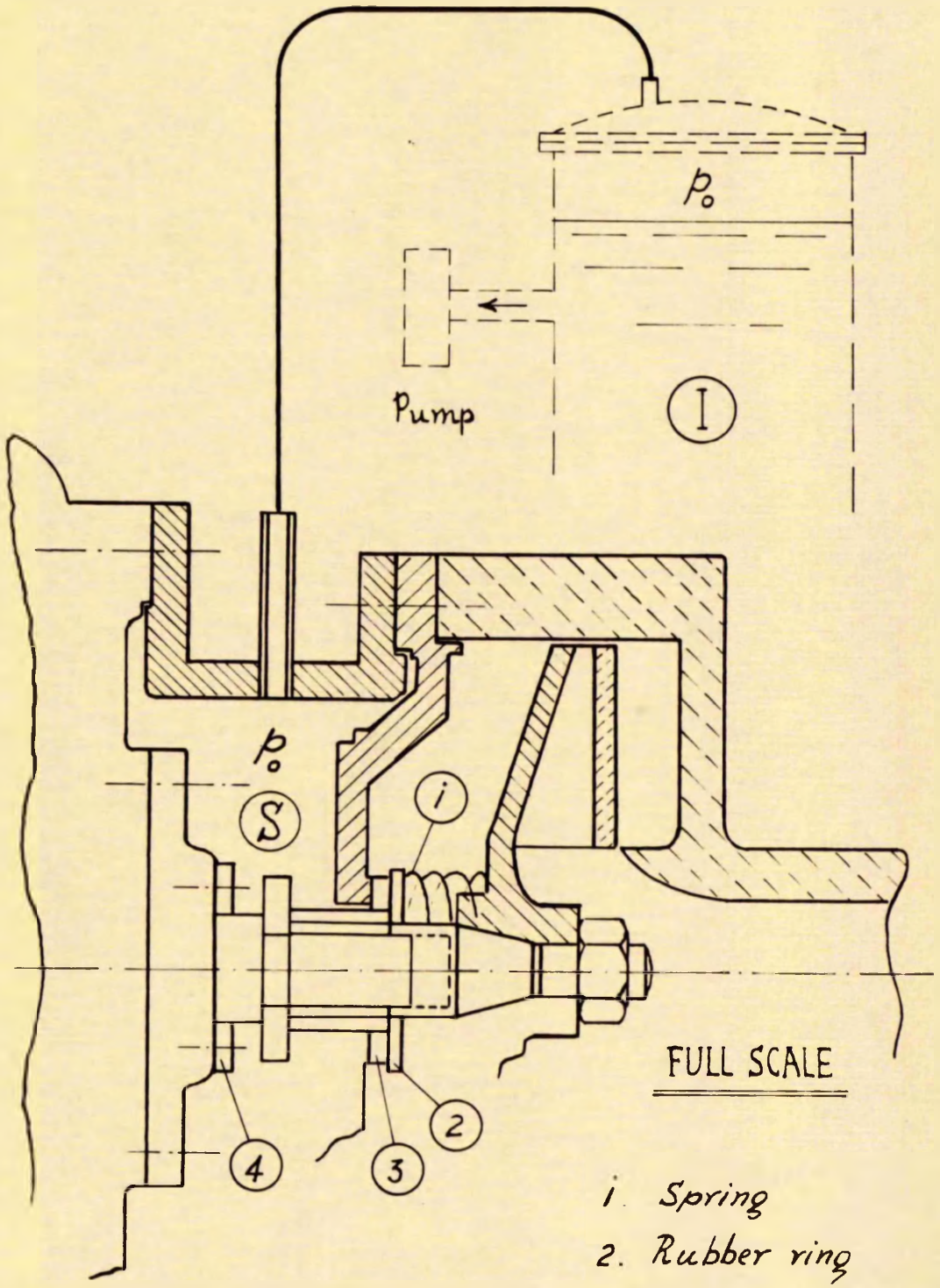
Pump Casing.

FIG. 5.



The Vacuum System

FIG. 6

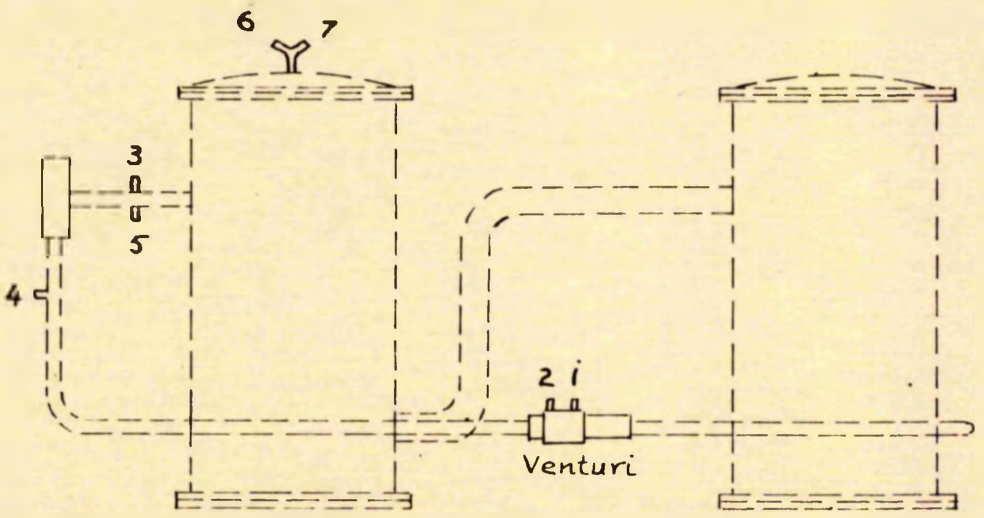


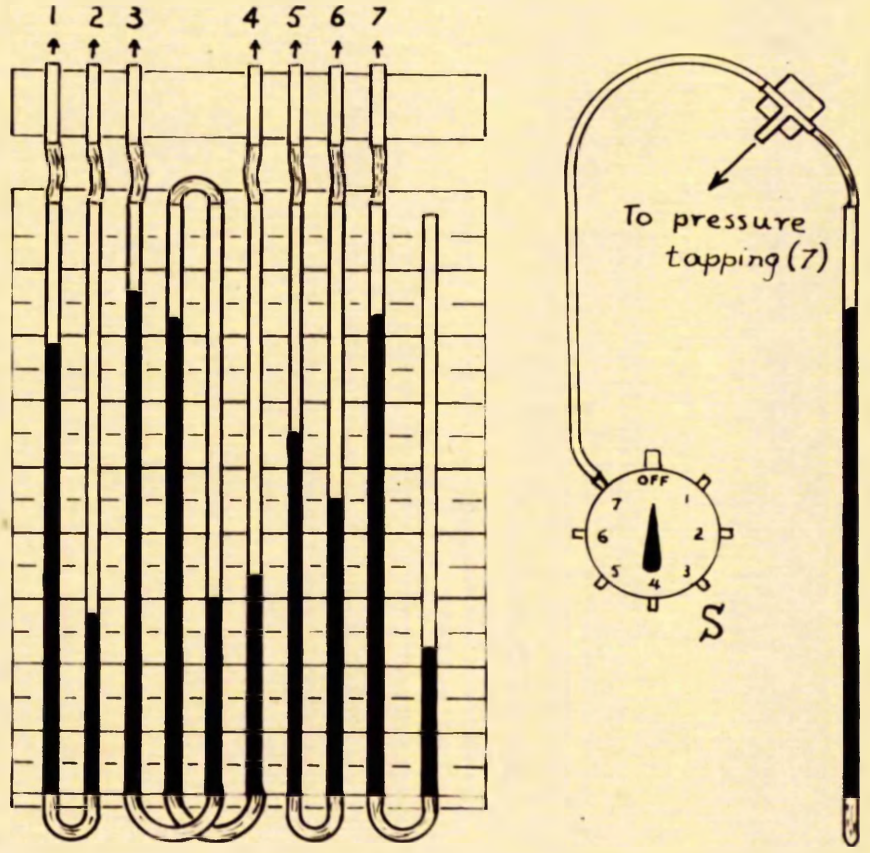
FULL SCALE

i. Spring
2. Rubber ring
3. Carbon ring
4. Leather ring

Device for stopping the leakage into the Pump casing.

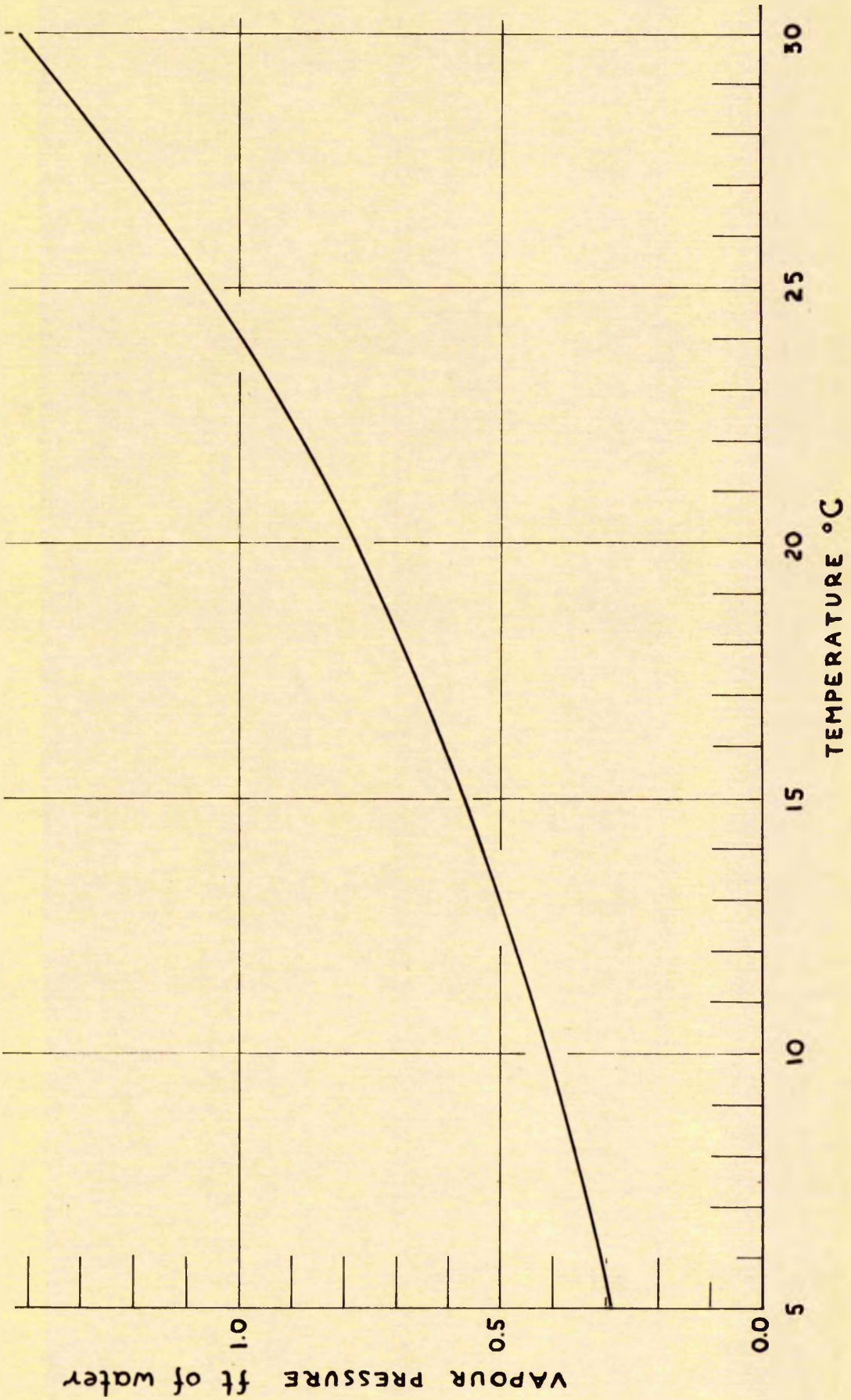
FIG. 7.





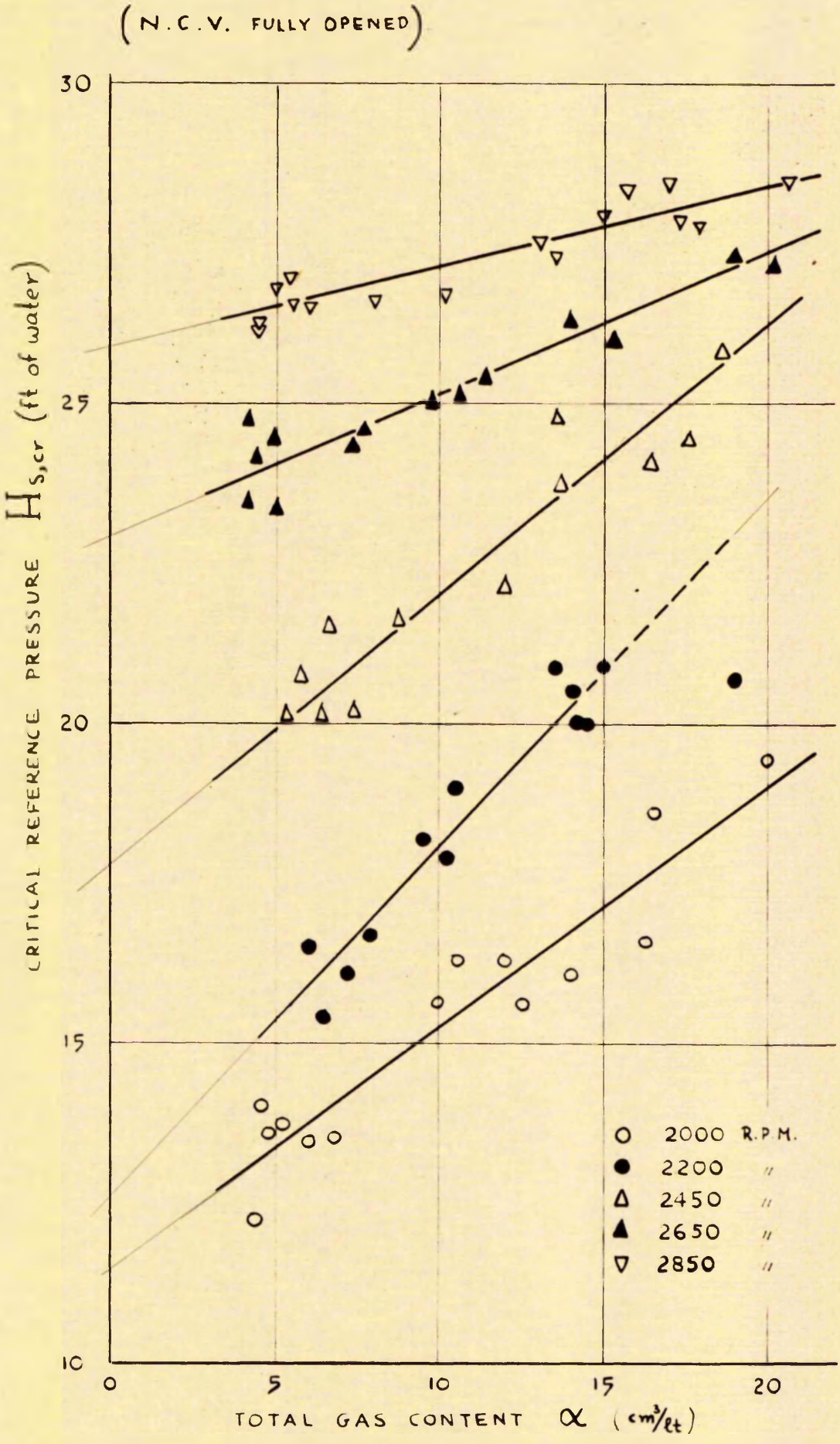
The Manometer

FIG. 8.



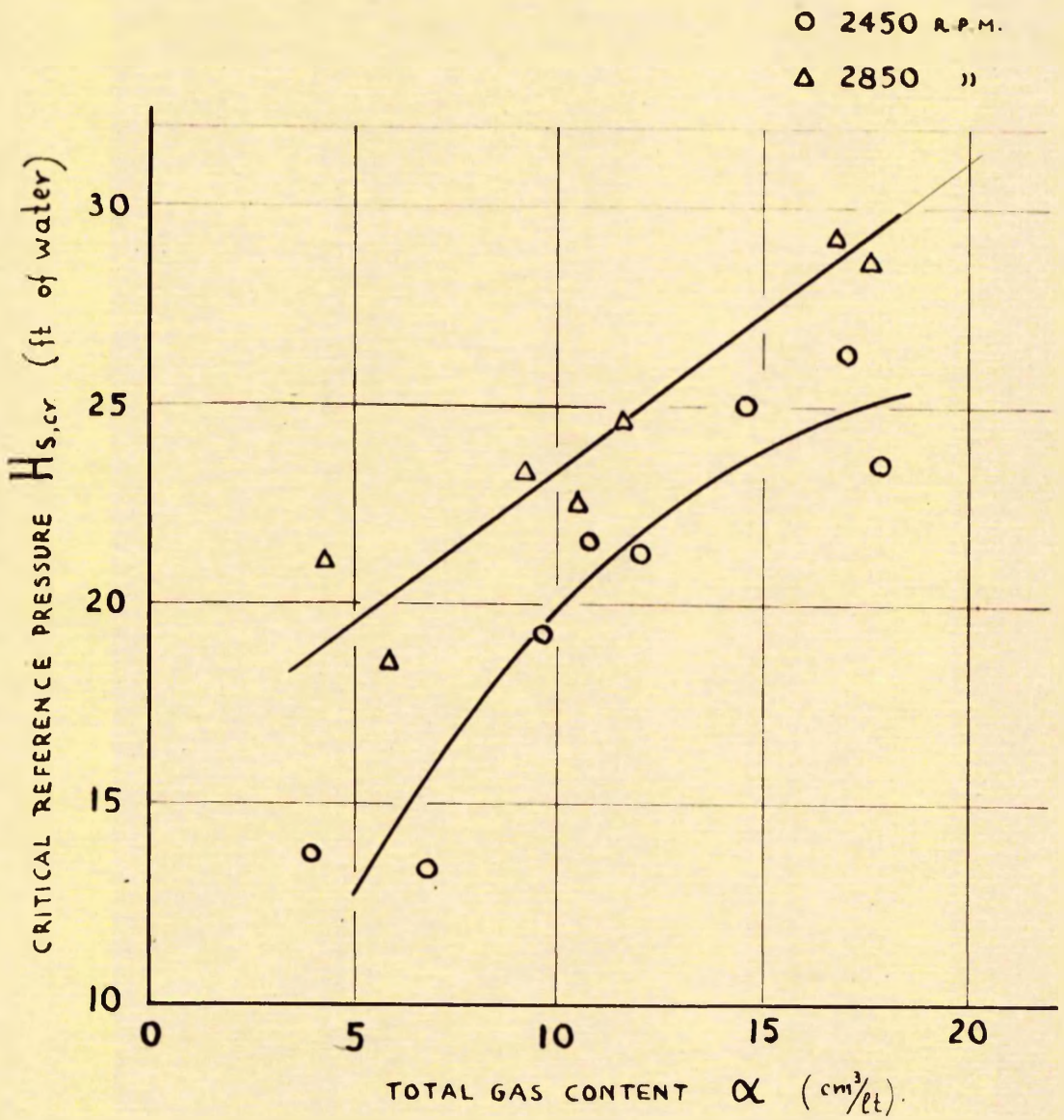
Variation of the Vapour Pressure of Water with Temperature.

FIG. 9.



Variation of $H_{S,cr}$ with α.

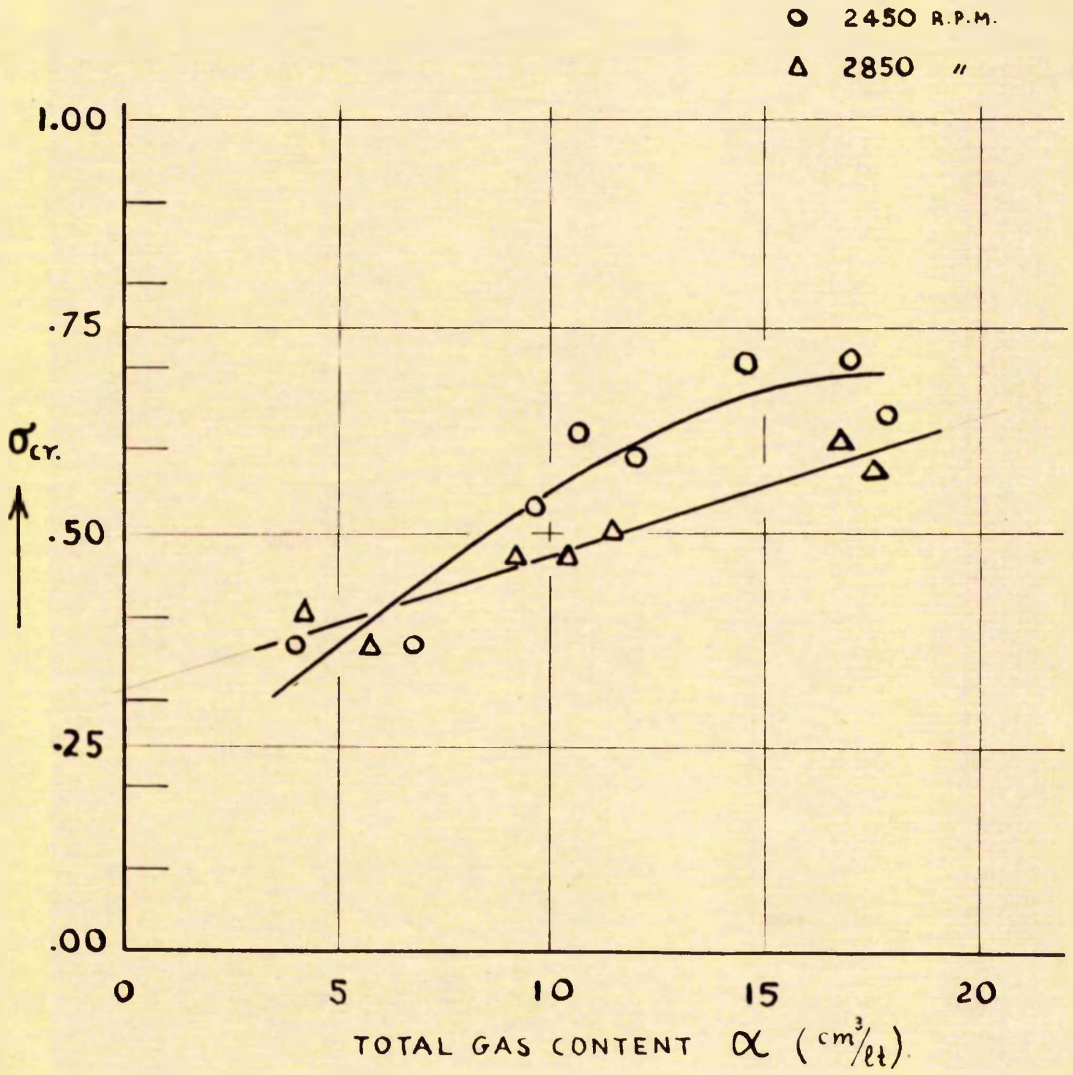
FIG. 10



(N.C.V. OPENED TO ALLOW 3/4 OF Q_{MAX})

Variation of $H_{s,cr.}$ with α.

FIG. 11.

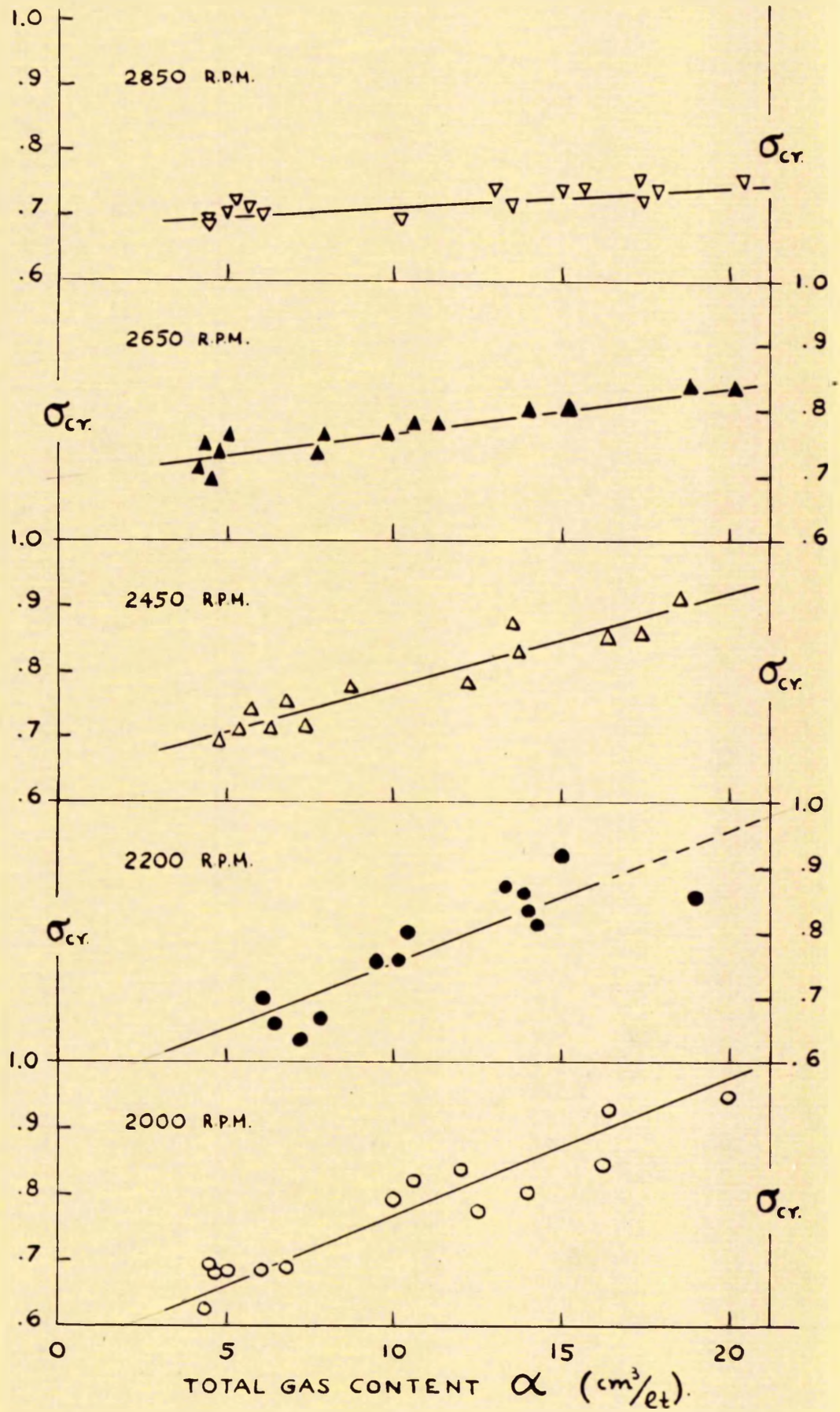


(N.C.V. OPENED TO ALLOW $^3/_4$ OF $Q_{MAX.}$)

Variation of $\sigma_{cr.}$ with α.

FIG. 12.

(N.C.V. FULLY OPENED).

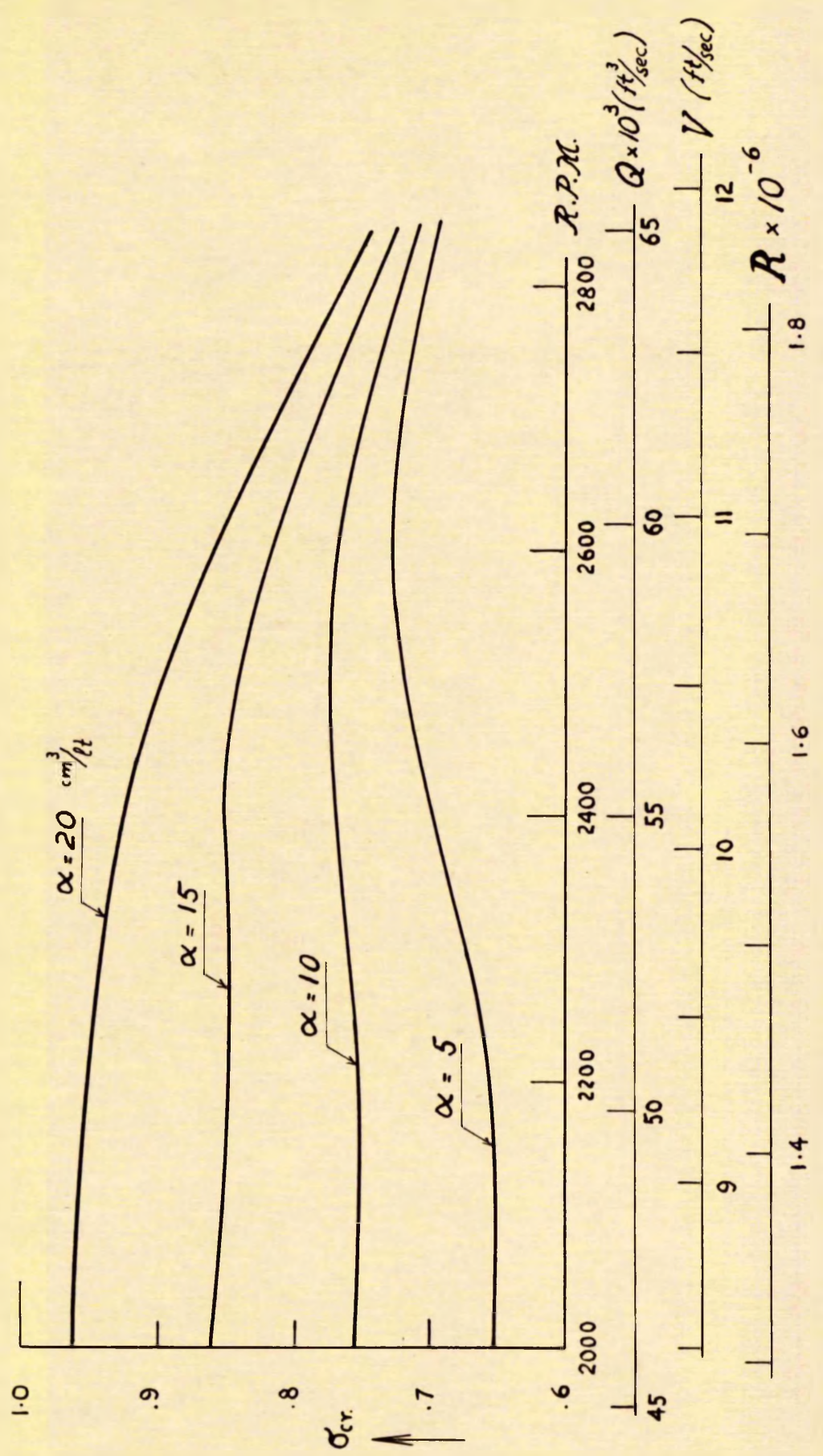


Variation of $\sigma_{cr.}$ with α.

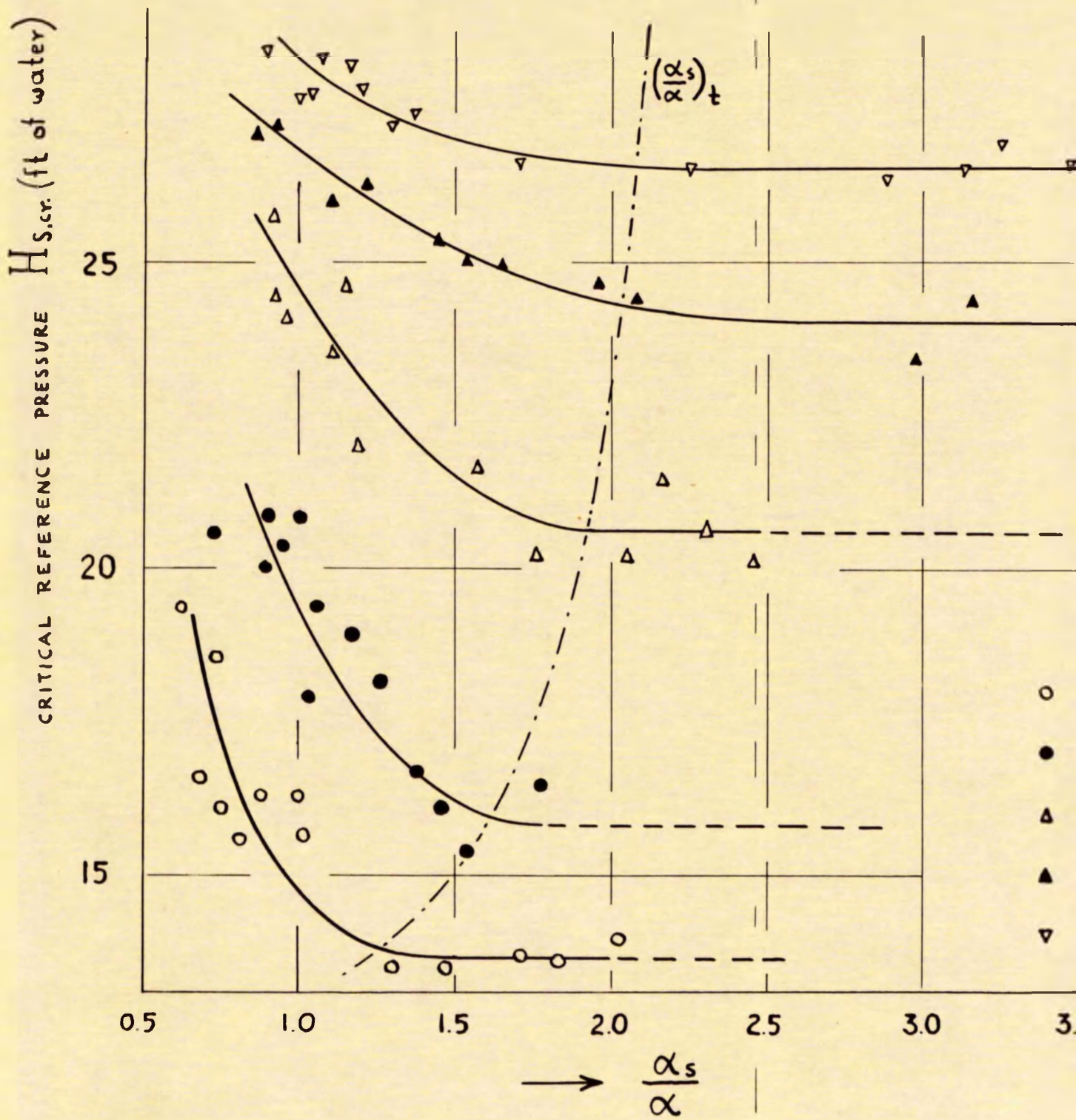
FIG. 13.

Variation of $H_{s,cr.}$ with R.P.M., Q, V, and R.

FIG. 14.

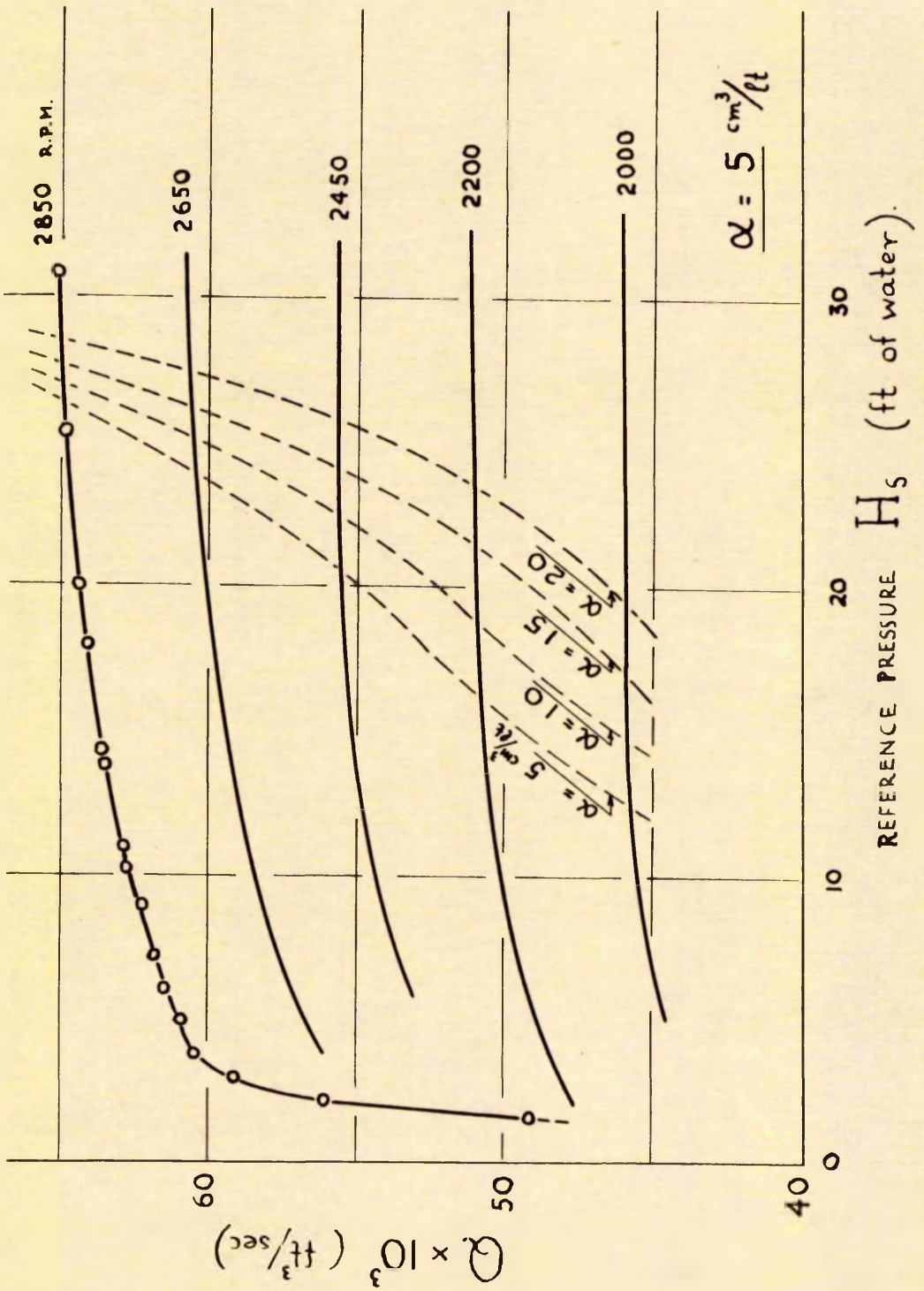


Variation of σ_{cr} with R.P.M., Q, V and R



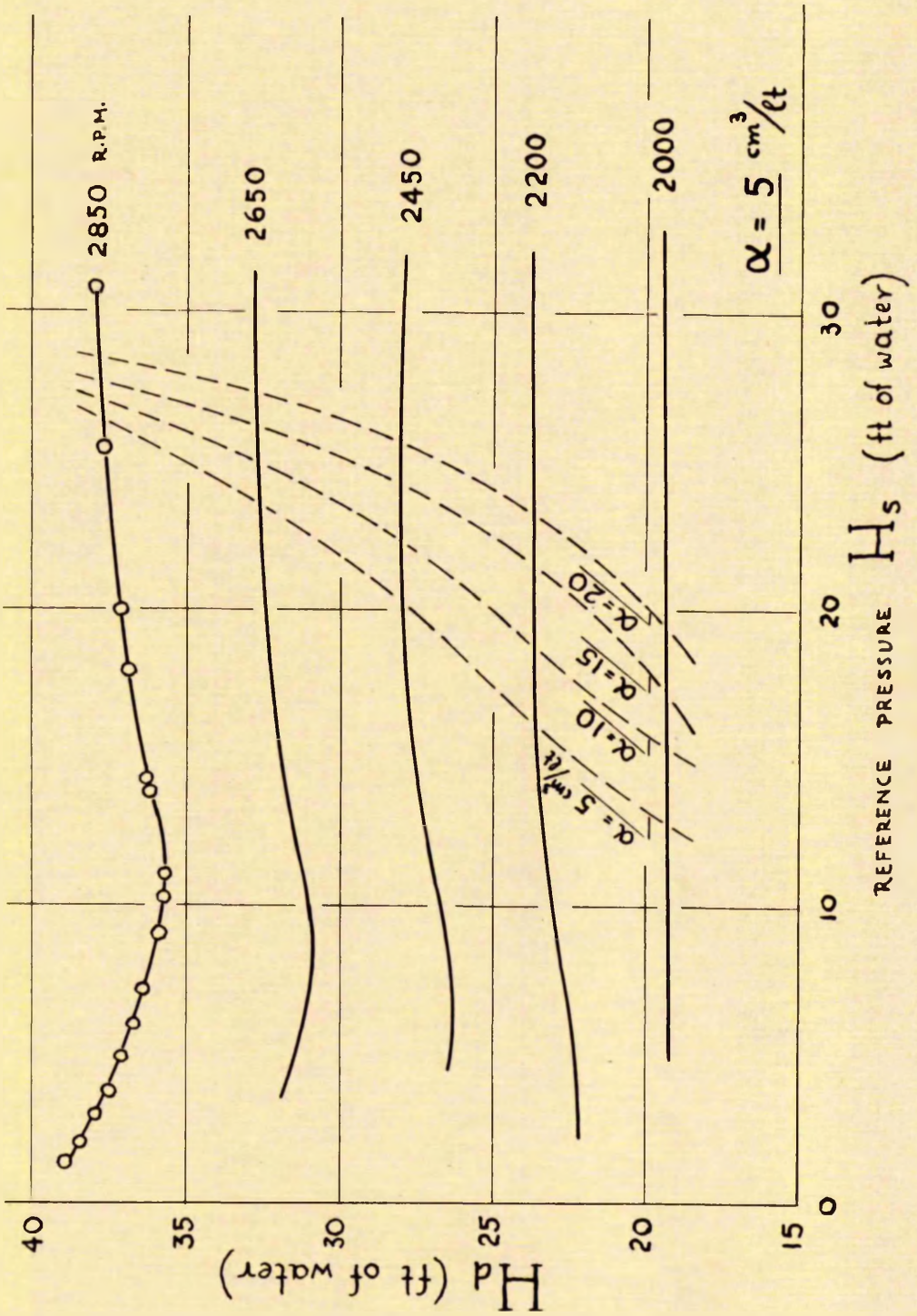
Variation of $H_{s,cr.}$ with $\frac{\alpha_s}{\alpha}$.

FIG. 16

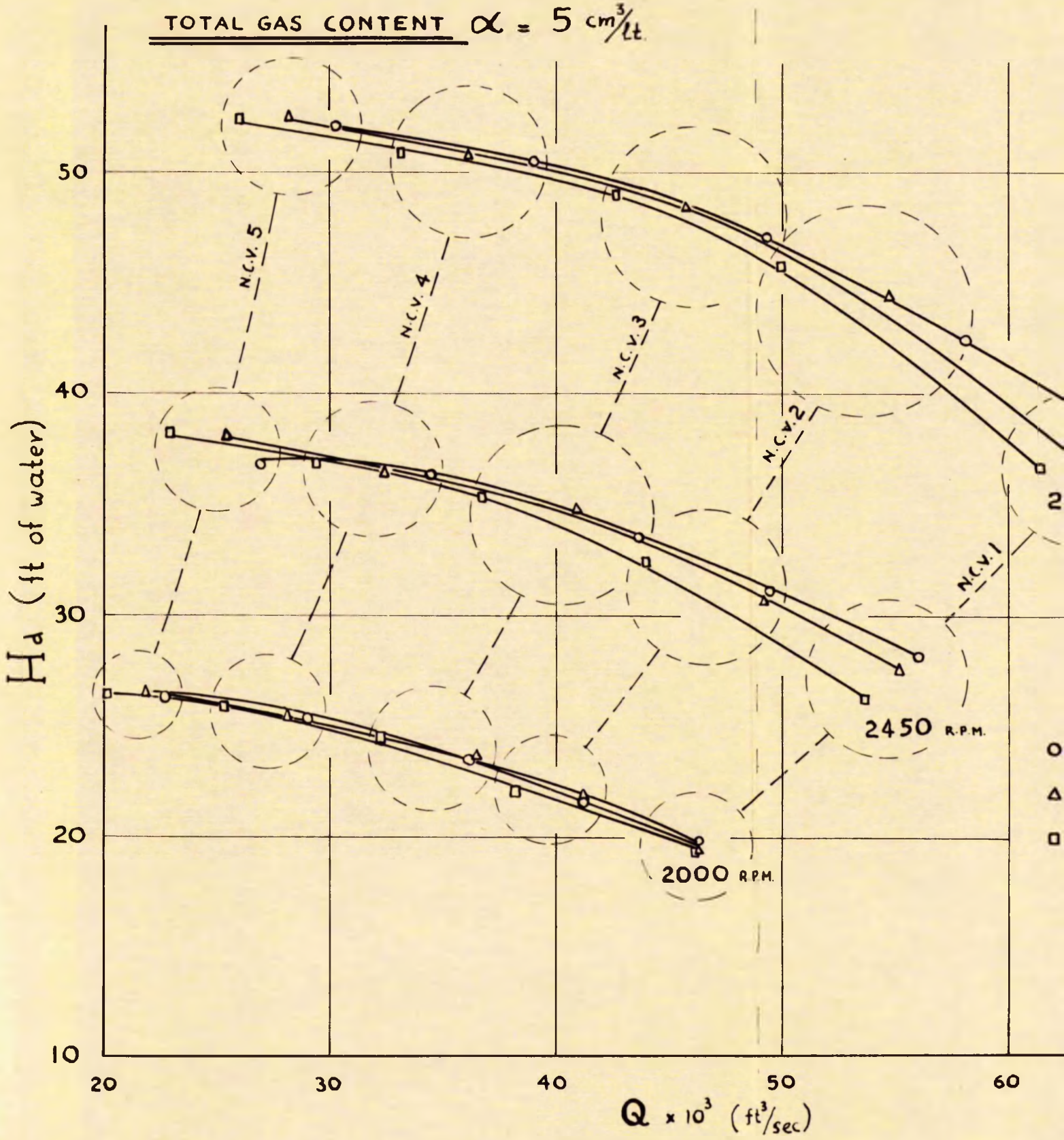


Variation of Q with H_s.

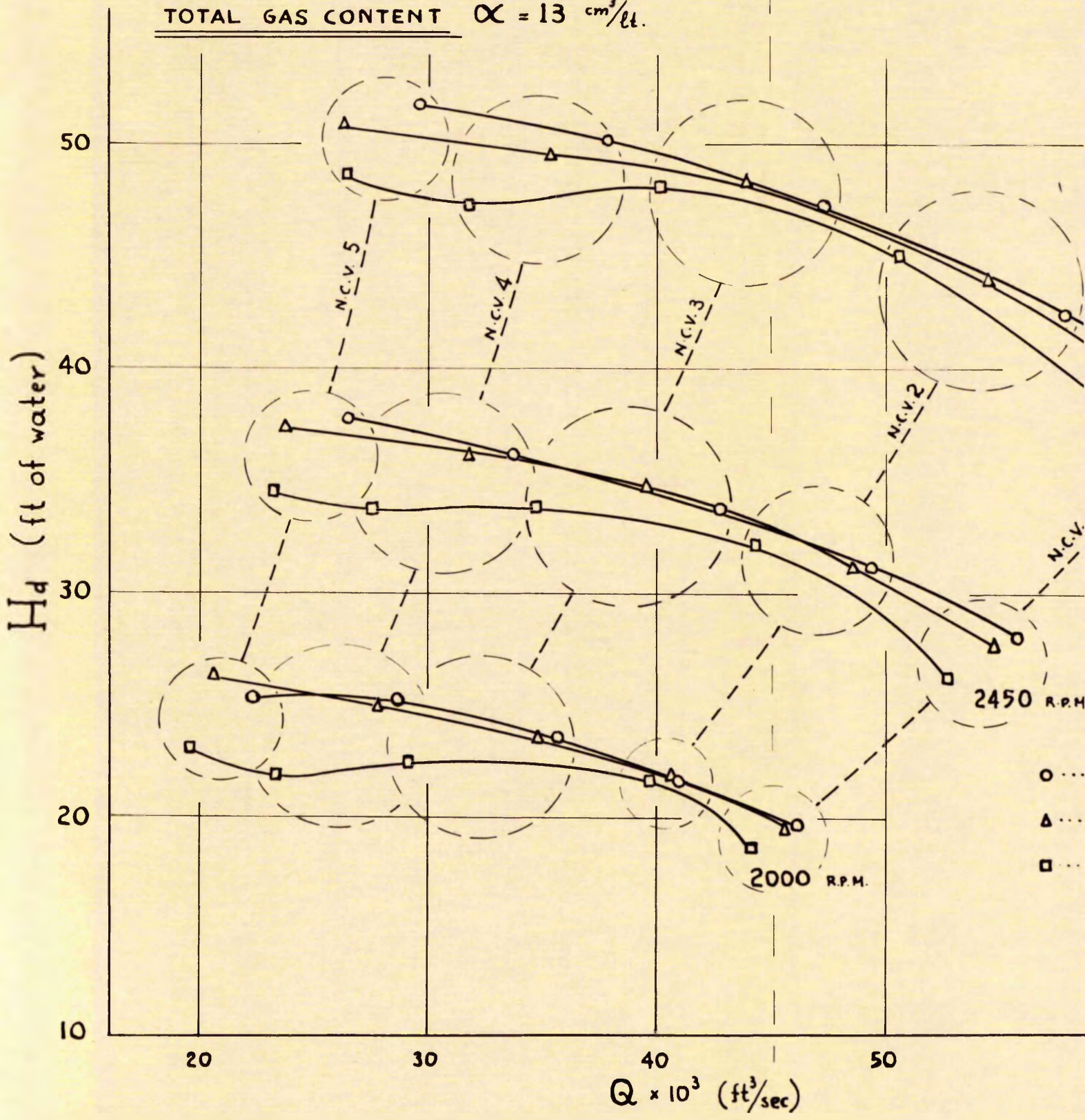
FIG. 17.



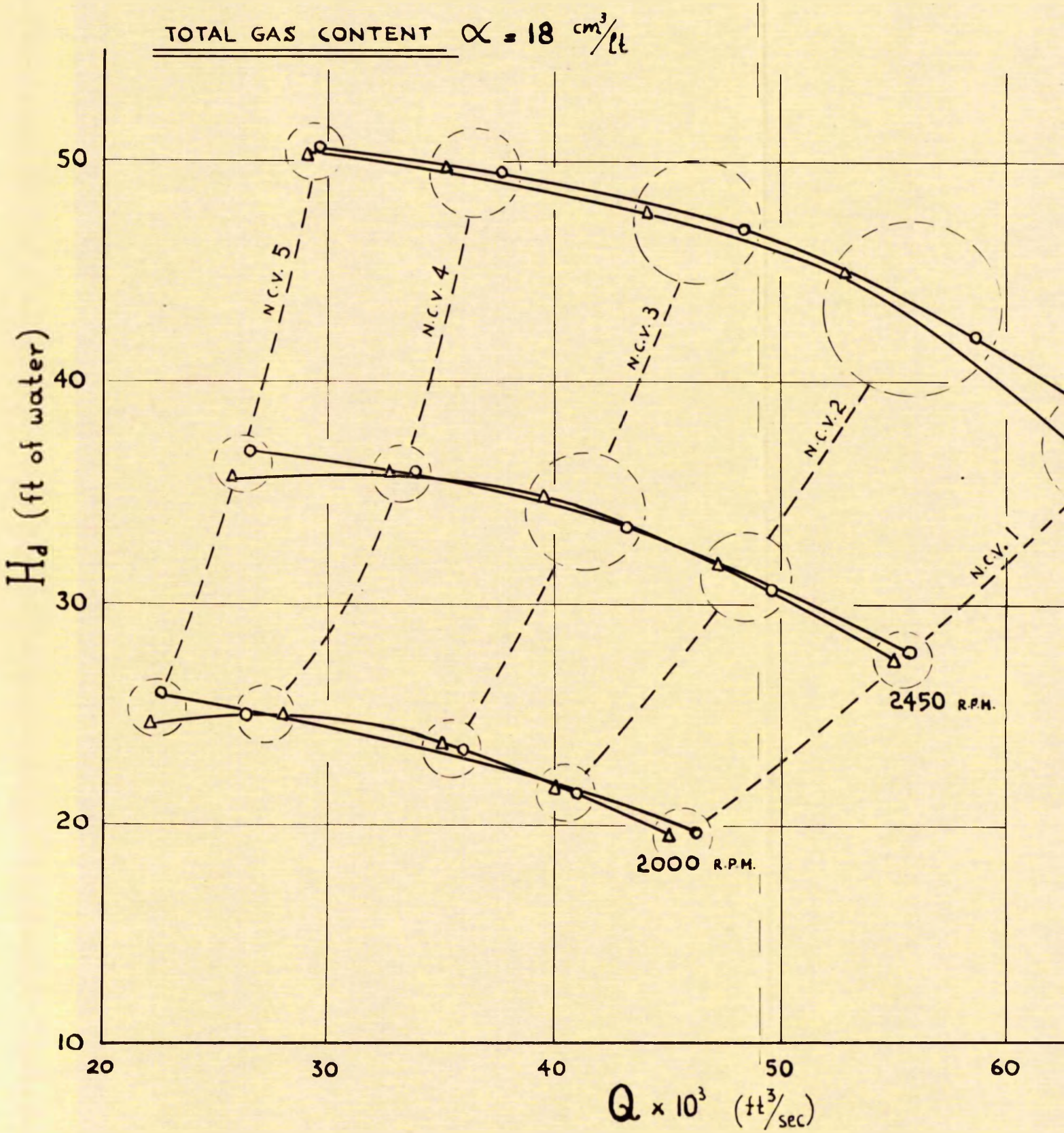
Variation of H_d with H_s.



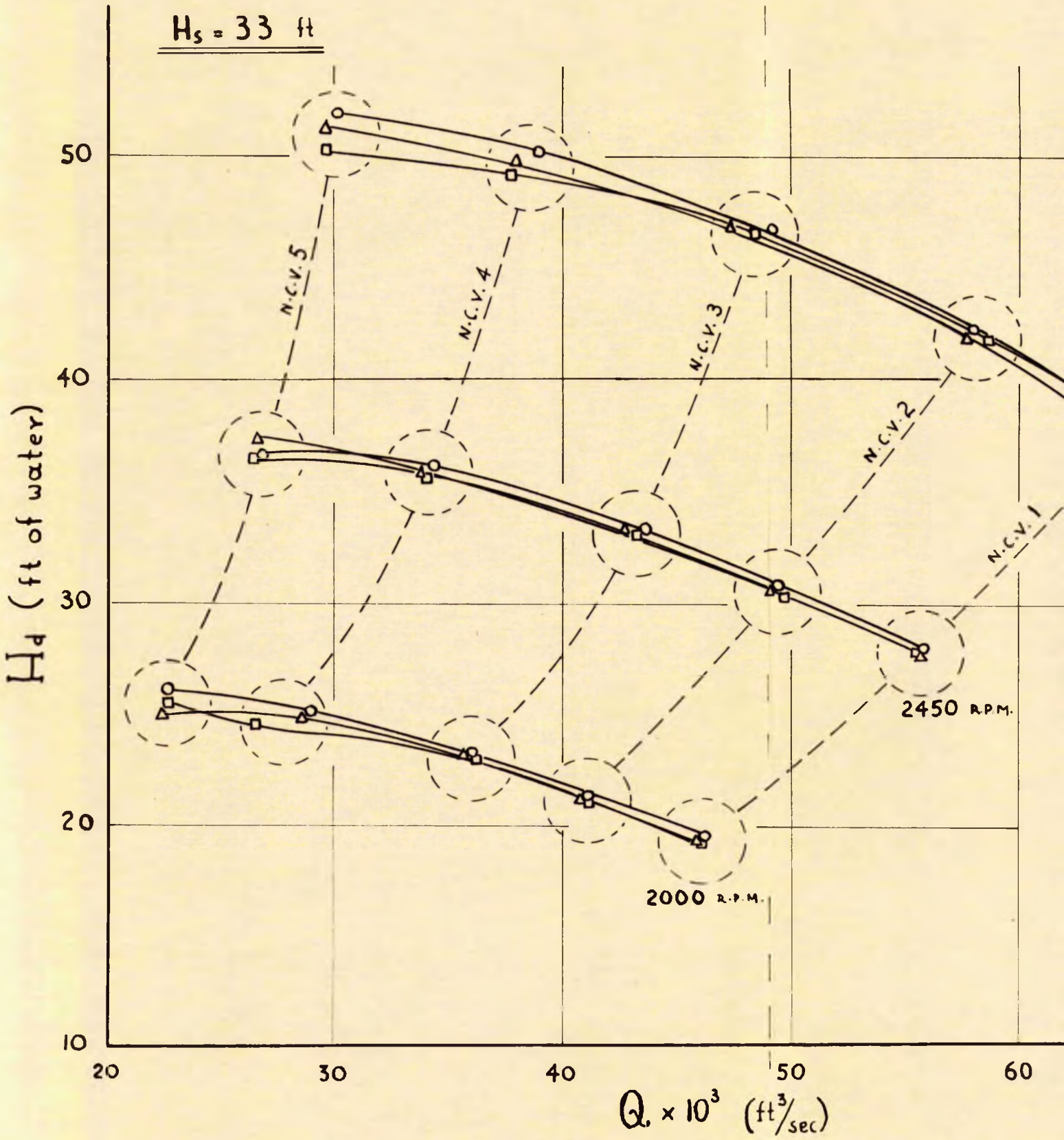
Variation of H_d with Q. α = 5 cm³/lt.



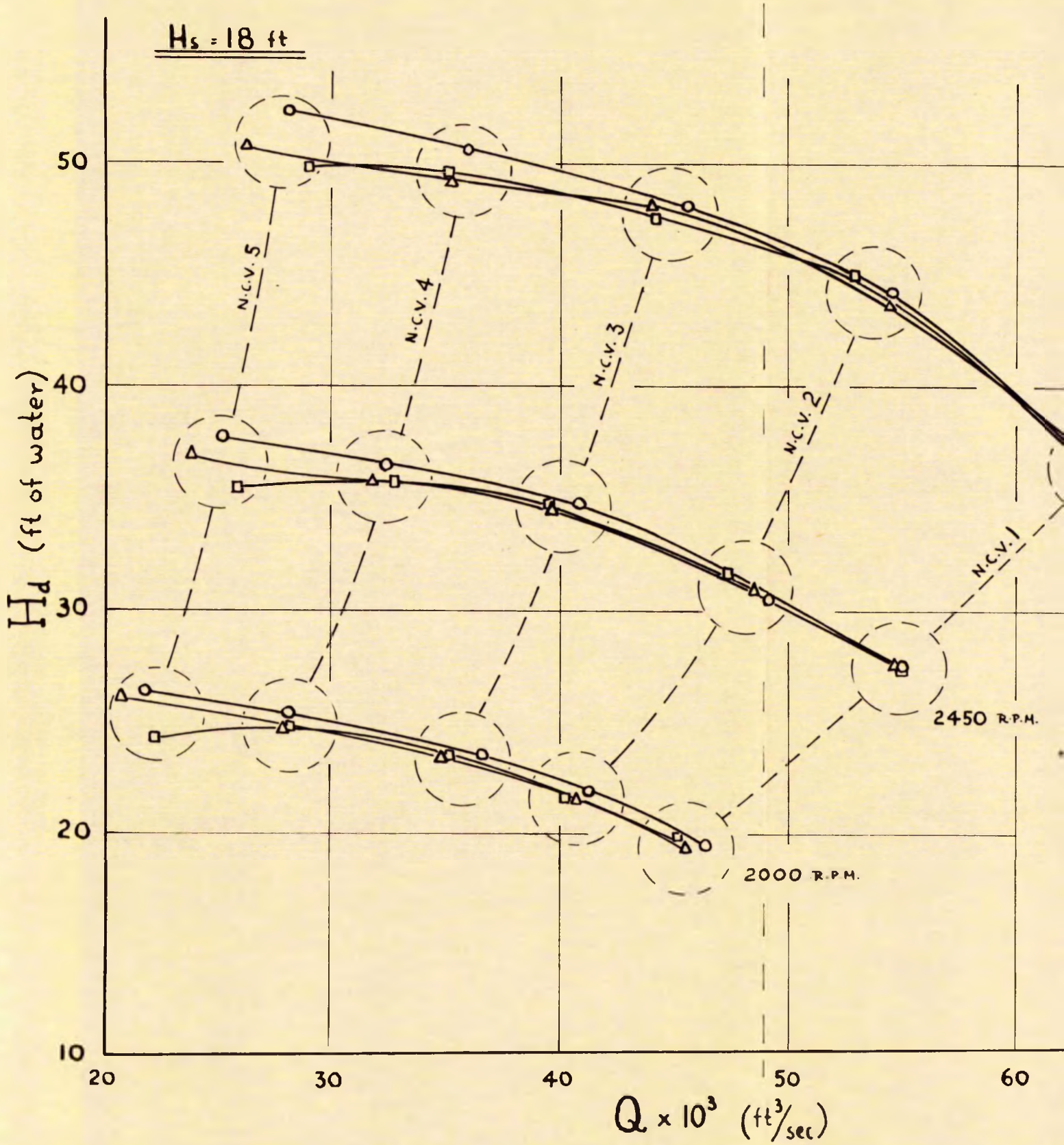
Variation of H_d with Q. α = 13 cm³/lt.



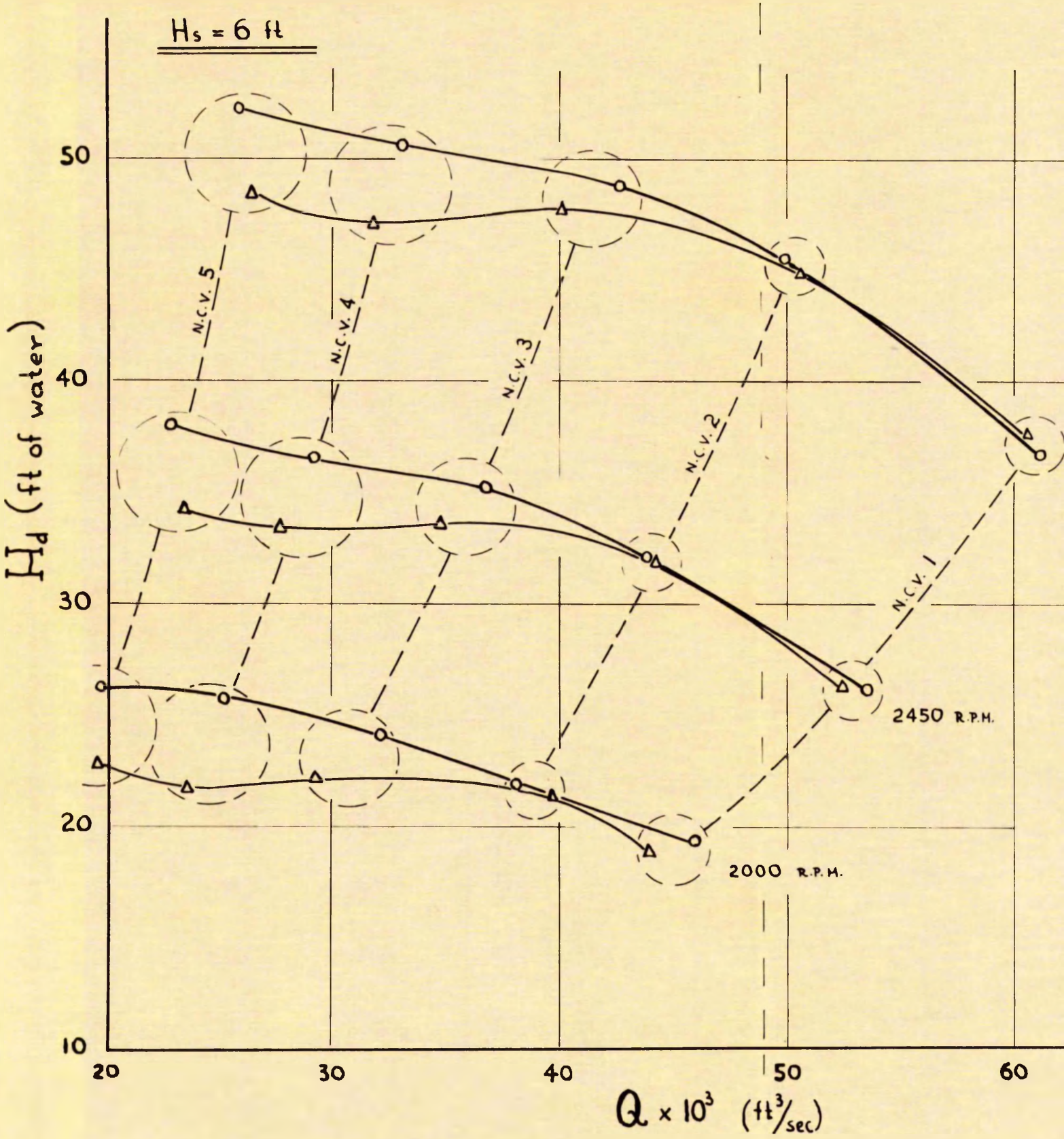
Variation of H_d with Q . α = 18 cm³/lt



Variation of H_d with Q. H_s = 33 ft.



Variation of H_d with Q. H_s = 18 ft.



Variation of H_d with Q . H_s = 6 ft .

FIG. 24.

2850 REV/MIN. NCV 1
σ = 0.022

2650 REV/MIN. NCV 1
σ = 0.041

2450 REV/MIN. NCV 1
σ = 0.059

2200 REV/MIN. NCV 1
σ = 0.091

2000 REV/MIN. NCV 1
σ = 0.129

1750 REV/MIN. NCV 1
σ = 0.187

1500 REV/MIN. NCV 1
σ = 0.282

1000 REV/MIN. NCV 1
σ = 0.720

800 REV/MIN. NCV 1
σ = 1.190

2850 REV/MIN. NCV 2
σ = 0.044

2450 REV/MIN. NCV 2
σ = 0.077

2000 REV/MIN. NCV 2
σ = 0.137

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MECHANICAL ENGINEERING RESEARCH LABORATORY
FLUID MECHANICS DIVISION

A Critical Survey of Methods for Measuring the Total Gas Content of Water

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APPENDIX I

March 1959

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DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

MECHANICAL ENGINEERING RESEARCH LABORATORY

A CRITICAL SURVEY OF METHODS FOR MEASURING THE TOTAL GAS CONTENT OF WATER

by

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(University of Glasgow)

SUMMARY

A theoretical analysis is made and the various methods are classified into two categories, the "direct methods" by which the total gas content is directly measured and the "indirect methods" by which the total gas content is computed from measurements of one of the constituents of the gaseous mixture. The only reliable methods in practice are the direct methods. A further method which could give a continuous indication of the total gas content would be an improved thermal conductivity method.

CONTENTS

1. INTRODUCTION

The principles governing the solution of gases in liquids have already been summarised[1].

The present work is an attempt to investigate theoretically the change in the composition of the dissolved gaseous mixture in water in hydraulic circuits, as a function of the total gas content, and to survey the possible and existing methods of determining this gas content.

The term "aeration" will be used to denote the process of increasing the dissolved gas content of the water in the circuit. Conversely the term "de-aeration" will denote the process of decreasing the dissolved gas content of the water.

2. VARIATION OF THE AMOUNT OF DISSOLVED GASES IN A CLOSED HYDRAULIC CIRCUIT

Consider a hydraulic circuit which contains water originally saturated with air under mean atmospheric conditions. Under static conditions the dissolved gas content changes only slightly with hydrostatic pressure. On the other hand under running conditions the dissolved gas content may vary with local hydrodynamic conditions. As a result the measured gas content of a sample of water taken from a fixed point in the circuit may not represent the "average" total gas content in the circuit.

2.1 Controlling Factors

The dissolved gas content of the circuit will be affected by a number of factors:

1. The total area of the water-gas interface A (free surface of water, gas nuclei cavitation zones, products of cavitation).
2. Volume of water in the circuit V.
3. The time t.
4. The partial pressures of the gaseous components in the gas phase P_1
5. The nature of the gases concerned G_1, G_2 ..... G_n.
6. The temperature θ.

2.2 General Equation

Provided that the liquid is kept uniformly mixed, the net rate at which a gas enters a liquid for any condition of area exposed, depth of liquid or degree of saturation is[1]:

$$\frac{dm}{dt} = (aP - bc)\, A \qquad (1)$$

where

dm is the amount of gas entering through an area A in the time interval dt,
P is the partial pressure of the gas in the gaseous space
C is the concentration of the gas in the liquid defined as mass of gas per unit volume of water
a is the entrance coefficient
b is the exit coefficient

Let C_1^0, C_2^0 .... C_n^0 be correspondingly the concentrations of the gases G_1, G_2, ... G_n at the time when the water is saturated under atmospheric conditions (t = o). Then the total concentration of gases dissolved in the water at time t = o will be given by:

$$C_0^0 = C_1^0 + C_2^0 + ... + C_n^0 \qquad (2)$$

Let now a_1, a_2, ... a_n be respectively the coefficients of entrance and b_1, b_2, ... b_n the coefficients of exit of the gases G_1, G_2, .. G_n. The new concentrations of the dissolved gases G_1, G_2, ... G_n at time t will be given by:

$$\left.\begin{aligned} C_1^t &= C_1^0 + \frac{1}{V} \int_0^t A\ (a_1P_1 - b_1C_1)\ dt \\ C_2^t &= C_2^0 + \frac{1}{V} \int_0^t A\ (a_2P_2 - b_2C_2)\ dt \\ &\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ C_n^t &= C_n^0 + \frac{1}{V} \int_0^t A_n(a_nP_n - b_nC_n)\ dt \end{aligned}\right\} \qquad (3)$$

and the total concentration at time t

$$C_0^t = C_1^t + C_2^t + ... C_n^t$$

$$= C_1^0 + C_2^0 + ... C_n^0 + \frac{1}{V} \int_0^t A \sum_{i=1}^{n} (a_1P_1 - b_1C_1)dt$$

or

$$C_0^t = C_0^0 + \frac{1}{V} \int_0^t A \sum_{i=1}^{n} (a_1P_1 - b_1C_1)dt \qquad (4)$$

Equation (4) holds for both "aeration" and "de-aeration" of the water of the circuit.

From equations (3) it follows that if

$$a_1 P_1 > b_1 C_1$$

"aeration" will take place and for a given magnitude of the partial pressure P_1 the greater the coefficient of entrance a_1 the larger is the amount of gas taken up by the water in a given interval of time dt or the quicker is the "aeration" of the water by this gas.

For "de-aeration" to take place

$$b_1 C_1 < P_1 a_1$$

3. VARIATION OF THE COMPOSITION OF THE DISSOLVED GAS CONTENT DURING CONTINUOUS DE-AERATION

Consider a quantity of pure water - volume V originally saturated with air under atmospheric conditions and let C_1^0, C_2^0 and C_3^0 be the original concentrations of carbon dioxide, oxygen and nitrogen respectively.

The extreme limit of de-aeration would be the case in which the gases released from the solution are carried away to the atmosphere through a high-vacuum pump of great capacity. In such a case the partial pressure of gases in the gaseous space is very small and in equation (1) the term aP may be neglected as being very small compared with the term bC. After this simplification equation (1) yields:

$$\frac{dm}{dt} = - bCA$$

and because

$$\frac{m}{V} = C$$

$$\frac{dC}{dt} = - bC \frac{A}{V} \qquad (5)$$

From which

$$\frac{dC}{C} = - b \frac{A}{V} dt$$

and

$$\frac{C}{C^0} = \exp \left(- b \frac{A}{V} t\right)$$

or

$$C = C^0 \exp \left(- b \frac{A}{V} t\right) \qquad (6)$$

For the gases in question equation (6) gives

$$\left.\begin{aligned} C_1 &= C_1^0 \exp\left(-b_1 \frac{A}{V} t\right) \\ C_2 &= C_2^0 \exp\left(-b_2 \frac{A}{V} t\right) \\ C_3 &= C_3^0 \exp\left(-b_3 \frac{A}{V} t\right) \end{aligned}\right\} \quad \text{.....(6a)}$$

and

$$C_0^t = C_1 + C_2 + C_3$$

$$= C_1^0 \exp\left(-b_1 \frac{A}{V} t\right) + C_2^0 \exp\left(-b_2 \frac{A}{V} t\right) + C_3^0 \exp\left(-b_3 \frac{A}{V} t\right) \quad \text{.....(7)}$$

Let us replace $\frac{A}{V} t$ by γ

$$\frac{A}{V} t = \gamma \quad \text{.....(8)}$$

and divide both terms of equation (7) by $C_1^0 + C_2^0 + C_3^0 = C_0^0$ then:

$$\varphi = \frac{C_0^t}{C_0^0} = \frac{C_1 + C_2 + C_3}{C_1^0 + C_2^0 + C_3^0} = \frac{C_1^0}{C_0^0} \exp(-b_1\gamma) + \frac{C_2^0}{C_0^0} \exp(-b_2\gamma) + \frac{C_3^0}{C_0^0} \exp(-b_3\gamma) \quad \text{.....(9)}$$

φ, being the ratio of the total gaseous concentration at time t, to that at time $t = 0$, is an index of the degree of de-aeration of the water.

From equation (1) it follows that if the water were saturated with a gas of partial pressure P then

$$\frac{dm}{dt} = (aP - bC^0) A = 0$$

i.e.
$$aP - bC^0 = 0 \quad \text{.....(10)}$$

or

$$C^0 = \frac{aP}{b} \quad \text{.....(11)}$$

For water saturated with air under mean atmospheric conditions and temperature 20°C, Table 1 gives the values of a, b and P for CO_2, O_2 and N_2.

Introducing the values of a, b and P from Table 1 into equation (11) the following values for the original concentrations of carbon dioxide, oxygen and nitrogen are found.

$$\left.\begin{aligned} CO_2 \text{ .... } C_1^0 &= 0.715 \text{ mg/litre} \\ O_2 \text{ .... } C_2^0 &= 9.550 \text{ mg/litre} \\ N_2 \text{ .... } C_3^0 &= 15.600 \text{ mg/litre} \end{aligned}\right\} \quad \text{.....(11a)}$$

and the total original gaseous concentration is

$$C_0^0 = C_1^0 + C_2^0 + C_3^0 = 25.865 \text{ mg/litre} \quad \text{(11b)}$$

Table 2 contains the solutions of the equations (6a), (7) and (9). In the first column of this table γ varies from 0 to 20 min/cm. In the 2nd to 4th columns the values of exp $(- b_1\gamma)$, exp $(- b_2\gamma)$ and exp $(- b_3\gamma)$ are given for the corresponding values of γ. In the 5th to 7th columns the values of C_1, C_2 and C_3 given by equations (6a) have been tabulated. In column 8 the values of the total gaseous concentration (C_0^t) for corresponding values of γ are given. In the 9th to 11th columns the variation of the ratios $\frac{C_1}{C_0^t}$ $\frac{C_2}{C_0^t}$ and $\frac{C_3}{C_0^t}$ have been included. These ratios denote the composition of the dissolved gaseous mixture for the given values of γ. Finally in the last column the values of $\varphi = \frac{C_0^t}{C_0^0}$ (degree of de-aeration) have been tabulated.

From this table the Figs. 1 and 2 have been plotted.

To obtain equation (6.) from equation (5), the area A was considered constant. In a hydraulic circuit, A is the total water-gas interface i.e. the area of the free surfaces of the water, the area of the surface of the gas nuclei, the area of the cavitation zones and the area of surface of the cavitation products (gas bubbles remaining and travelling after the collapse of the cavitation cavities). The assumption for perfect mixing of the water requires circulation of the water in the circuit. Due to the very low pressure under which the de-aeration has been supposed to take place, intense cavitation will occur during the circulation of the water. As the de-aeration proceeds the intensity of cavitation will be reduced gradually due to reduction of gas content. This will result in gradual reduction of the total free surface area A and the time required for the de-aeration of the water down to a given degree will be somewhat greater than the corresponding times given by the previous analysis. However this gradual reduction in A will not affect the dissolved gaseous mixture composition to degree of de-aeration relation as can be seen from the form of equation (1).

Table 2 shows that the de-aeration is very rapid for small values of γ (i.e. at the beginning of the de-aeration) with a continuously decreasing rate of evolution of gases from the solution.

Under saturation conditions the concentration of the dissolved carbon dioxide (C_1) is a small percentage of the oxygen or nitrogen concentrations. As the de-aeration proceeds (total gas content decreasing) C_1, C_2 and C_3 are continuously decreasing but C_1 decreases at a much smaller rate and for a value of $\gamma \simeq 7.5$ min/cm^2 corresponding to a value of $\varphi = 2.5$ per cent, the concentrations of the three gases in the water become of the same order of magnitude. If de-aeration were continued further carbon dioxide would become the predominant gas in solution.

A better picture of the composition of the dissolved gaseous mixture is obtained by plotting $\frac{C_1}{C_0 t}$, $\frac{C_2}{C_0 t}$ and $\frac{C_3}{C_0 t}$ against φ (Fig. 2). From this figure it can be seen that $\frac{C_1}{C_0 t}$ increases while both $\frac{C_2}{C_0 t}$ and $\frac{C_3}{C_0 t}$ decrease as φ is decreased.

4. VARIATION OF THE COMPOSITION OF THE DISSOLVED GAS CONTENT DURING CONTINUOUS AERATION

Suppose now that a quantity of pure water originally de-aerated to a given degree is brought into an atmosphere of a gaseous mixture, the composition and partial pressure of which remain constant (as for example, when the free surface of the water is exposed to the atmospheric air). Then aeration of the water will take place until the concentrations of the gases in solution are in equilibrium under the partial pressures of the gases in the gaseous space (Henry's Law).

Equation (1) can be written:

$$\frac{dC}{dt} = (aP - bC)\frac{A}{V} = a\frac{A}{V}P - b\frac{A}{V}C$$

Following the previous assumption $a\frac{A}{V}P$ is a constant and because $b\frac{A}{V}$ is a constant (a, b are constant for given temperature and given gas of the mixture)

$$\frac{dC}{dt} = \varepsilon - \lambda C \qquad (12)$$

where

$$\frac{aAP}{V} = \varepsilon = \text{const. and } b\frac{A}{V} = \lambda = \text{const.} \qquad (13)$$

From (12)

$$\frac{dC}{\varepsilon - \lambda C} = dt$$

or

$$\frac{d(\lambda C - \varepsilon)}{\lambda C - \varepsilon} = -\lambda dt$$

or

$$\log(\lambda C - \varepsilon) + K = -\lambda t \qquad (14)$$

where K is a constant.

Now when $t = 0$ let

$$C = C^*$$

C^* = original concentration.

Then

$$K = - \log (\lambda C^* - \varepsilon)$$

and

$$\log (\lambda C - \varepsilon) - \log (\lambda C^* - \varepsilon) = - \lambda t$$

or
$$\log \frac{\lambda C - \varepsilon}{\lambda C^* - \varepsilon} = - \lambda t \qquad (15)$$

and

$$\frac{\lambda C - \varepsilon}{\lambda C^* - \varepsilon} = \exp (- \lambda t) \qquad (16)$$

from which

$$\lambda C = (\lambda C^* - \varepsilon) \exp (- \lambda t) + \varepsilon$$

and

$$C = (C^* - \frac{\varepsilon}{\lambda}) \exp (- \lambda t) + \frac{\varepsilon}{\lambda}$$

$$= C^* \exp (- \lambda t) + \frac{\varepsilon}{\lambda} (1 - \exp (- \lambda t)) \qquad (17)$$

or

$$\frac{C}{C^*} = \exp (- \lambda t) + \frac{\varepsilon}{\lambda C^*} (1 - \exp (- \lambda t)) \qquad (18)$$

But

$$\frac{A}{V} t = \gamma \text{ (equation 8)}$$

and

$$b \frac{A}{V} = \lambda \text{ (equation 13).}$$

Thus

$$\lambda = \gamma \frac{b}{t} \qquad (19)$$

Now $\varepsilon = \frac{aAP}{V} = \frac{aP\gamma}{t}$ from equations (8) and (13),

and so

$$\frac{\varepsilon}{\lambda C^*} = \frac{\frac{aP\gamma}{t}}{\gamma\, b/_t\, C^*} = \frac{aP}{bC^*} \qquad \text{.....(20)}$$

Therefore (18) takes the form:

$$\frac{C}{C^*} = \exp\,(-\gamma b) + \frac{aP}{bC^*}\,(1 - \exp\,(-\gamma b)) \qquad \text{.....(21)}$$

NOTE: if $P = 0$ and $C^* = C^0$ then equation (17) becomes

$$\frac{C}{C^0} = \exp\,(-\lambda t)$$

which is the form of equation (6.) because $\lambda = b\,\frac{A}{V}$

4.1 Aeration from φ = 2 per cent

Suppose when $t = 0$ that the total dissolved gas content is about 2 per cent of that corresponding to saturation at atmospheric conditions, and that the water is exposed to atmospheric air.

Then from Table 2 and for φ = 2.08 per cent

$$\left.\begin{aligned} C_1^* &= 0.212 \text{ mg/litre} \\ C_2^* &= 0.129 \text{ mg/litre} \\ C_3^* &= 0.197 \text{ mg/litre} \end{aligned}\right\} \qquad \text{.....(22)}$$

Substituting the values of C_1^*, C_2^* and C_3^* from (22) and the values of a, b and P from Table 1 into expression (20) we obtain:

$$\left.\begin{aligned} CO_2 \;\ldots\; a_1P_1/b_1C_1^* &= 3.37 \\ O_2 \;\ldots\; a_2P_2/b_2C_2^* &= 74 \\ N_2 \;\ldots\; a_3P_3/b_3C_3^* &= 79.3 \end{aligned}\right\} \qquad \text{.....(23)}$$

Thus for the gases under consideration equation (21) gives:

$$\left.\begin{aligned} CO_2 \ldots\ & \frac{C_1}{C_1^*} = 3.37 - 2.37 \exp(-0.152\gamma) \\ O_2 \ldots\ & \frac{C_2}{C_2^*} = 74 - 73 \exp(-0.536\gamma) \\ N_2 \ldots\ & \frac{C_3}{C_3^*} = 79.3 - 78.3 \exp(-0.546\gamma) \end{aligned}\right\} \quad \ldots\ldots (24)$$

where γ should be expressed in min/cm.

The solutions of these equations have been tabulated in Table 3. In the first column of this table γ is given. In the 2nd to 4th columns the values of C_1, C_2 and C_3 as found from equation (24) for the corresponding values of γ are tabulated. In the 5th column the total gaseous concentration is given while column 6 shows the calculated values of φ. Finally the three last columns give the ratios $\frac{C_1}{C_0 t}$, $\frac{C_2}{C_0 t}$ and $\frac{C_3}{C_0 t}$.

4.2 Aeration starting from $\varphi = 0$ (completely de-aerated water)

For completely de-aerated water

$$C^* = 0$$

and equation (21) becomes

$$C = \frac{aP}{b}(1 - \exp(-\gamma b)) \quad \ldots\ldots (25)$$

From (11) $\frac{aP}{b} = C^0$. The values of C^0 for CO_2, O_2 and N_2 are given by equations (11a).

Thus:

$$\left.\begin{aligned} C_1 &= 0.715\,(1 - \exp(-\gamma b_1))\ \text{mg/litre} \\ C_2 &= 9.55\,(1 - \exp(-\gamma b_2))\ \text{mg/litre} \\ C_3 &= 15.60\,(1 - \exp(-\gamma b_3))\ \text{mg/litre} \end{aligned}\right\} \quad \ldots\ldots (26)$$

The solutions of equation (26) have been tabulated in Table 4 which is similar in form to Table 3.

From Tables 2, 3 and 4 the following diagrams have been plotted.

Fig. 1. shows the variation of C_1, C_2, C_3 and $C_0{}^t$ with γ
(a) for de-aeration starting from φ = 100 per cent
and (b) for aeration starting from φ = 0 per cent.

Fig. 2. shows the variation of $\frac{C_1}{C_0{}^t}$, $\frac{C_2}{C_0{}^t}$ and $\frac{C_3}{C_0{}^t}$ with φ
(a) for de-aeration starting from φ = 100 per cent
(b) for aeration starting from φ = 2 per cent
and (c) for aeration starting from φ = 0 per cent.

and Fig. 3. shows the variation of error with φ resulting from calculating the total dissolved gas content by assuming a definite variation of oxygen content with the degree of de-aeration (i.e. total dissolved gas content).

5. PRACTICAL LIMITATIONS OF THE ANALYSIS

As can be seen from the tables and figures of the theoretical analysis the composition of the dissolved gaseous mixture varies with the variation of the total amount of gases dissolved. Moreover this variation is not a simple function of the total dissolved gas content. It depends on whether the process is aeration or de-aeration.

The theoretical analysis for the determination of the composition of the gaseous mixture dissolved in the water was based, for the sake of simplicity, on a number of assumptions:

(i) The water was assumed to be saturated with air under mean atmospheric conditions and at temperature 20°C.

(ii) The water was assumed to be pure.

(iii) The temperature of the aqueous and gaseous phase was assumed to be kept constant at 20°C.

(iv) It was assumed that no leakages of air into the circuit occurred while the circuit was being operated under vacuum.

None of the above conditions is strictly fulfilled in operation of a hydraulic circuit. Deviations from the imposed simplified assumptions will result, in general, in further complicated and irregular variations in the composition of the dissolved gaseous mixture as a function of the total dissolved gas content.

In particular:

A change in atmospheric conditions will affect the original composition of the saturated solution, and the operating liquid in hydraulic circuits is never perfectly pure water. A change in the physical and/or chemical properties of

the operating liquid will alter the values of the coefficients of entrance and exit on which the composition of the dissolved gaseous mixture mainly depends. The composition of the dissolved gases might also be upset if the water of the circuit were contaminated. Bacteria feeding on organic material in the water of the circuit could absorb a large fraction of the dissolved oxygen. Measurements made by the Cambridge Instrument Company in Ossining, New York, indicate that tap water is only 80 per cent saturated with oxygen (Borden[2]). Table 5 taken from Numachi[3] shows the compositions of the dissolved gases from actual measurements for a number of samples of water taken from various sources.

The temperature coefficient of the coefficients of entrance and exit of the gases under consideration (CO_2, O_2, N_2) differs appreciably from one gas to another and the temperature has a great effect on the composition of the dissolved gases.

Finally leakages of air into the circuit will upset the composition of the dissolved gaseous mixture given by the previous analysis, because the composition of the atmospheric air is much different from any possible composition attainable by the dissolved gaseous mixture.

6. METHODS FOR THE DETERMINATION OF THE TOTAL GAS CONTENT

The total gas content in water influences several of its physical properties such as its density, compressibility, surface tension, tensile strength, conductivity, refractive index, light absorption and the inception of cavitation. However changes in most of these is either very slight or depends mainly on the composition of the dissolved gaseous mixture. This imposes a limit in the possible number of methods which could be used with acceptable accuracy for the determination of the total gas content of water samples.

The methods which have been used can be classified under two headings (i) direct and (ii) indirect methods.

6.1 Direct Methods

These methods are usually called extraction methods. Such methods have been developed by Van Slyke[4], Williams[5], Shal'nev[6] and by the author[1,7].

In all of these methods the total gas content of a sample of water is extracted by subjecting the sample to a vacuum (of the order of the vapour pressure of the water) and repeatedly spraying or continuously shaking it. The pressure of the released gases constrained in a given volume is measured. With the improved extraction method developed by the author[1] the total gas content of the water of a hydraulic circuit at any condition can be measured with an accuracy of ± 1 per cent.

6.2 Indirect Methods

In this category are included all the methods which are based on measurement of the amount of one of the gaseous constituents dissolved in the water. The corresponding total gas content is afterwards found by calculation. The Winkler chemical method determines the total gas content from measurements of

the dissolved oxygen content; other methods are dissolved oxygen recorders and photometric determination of dissolved oxygen content. These methods have been adopted for either laboratory or industrial purposes.

Other suggested methods are the polarographic method; (a method based on measurements of the electrical conductivity of the water-gas solution), and a thermal conductivity method (based on measurements of the thermal conductivity of the gases released from solution).

It has been shown already that even for pure water the composition of the dissolved gaseous mixture is neither constant nor follows a definite law with changes in total dissolved gas content. Moreover, the variation increase if the water is not pure or if liquids other than water are used. In addition variation in temperature makes the calculation of the total gas content from such measurements very complicated.

All the indirect methods are, therefore, bound to have a low accuracy which becomes worse for small gas contents. Fig. 3 shows the variation of the accuracy of a method based on oxygen content measurements for the calculation of the total gas content, plotted against φ. From this figure and for φ = 10 per cent the error is ± 5 per cent while for φ = 2 per cent the error may be as large as ± 23 per cent, and it must be emphasized that Fig. 3 only considers the theoretical limitations without considering the practical errors.

These remarks refer in general to all the indirect methods. The following limitations are imposed in certain cases.

(i) **Polarographic Method:** The dissolved oxygen content is measured and the gas content obtained by calculation. Its application for measurement of total gas content is not advisable because in addition to the general disadvantages of the indirect methods, it is greatly affected by contaminations in the water. The presence of solid particles and other matter in suspension in the sample of water quickly causes contamination of the electrodes.

(ii) **Photometric Method:** This also determines the dissolved oxygen, but can be used for concentrations up to only 0.10 mg/litre of dissolved oxygen (which corresponds to about φ = 1.5 per cent). Consequently this method cannot be used for the determination of the gas content of the water in hydraulic circuits.

(iii) **Electrical Conductivity Method:** The change of the electrical conductivity of the water-gas solution with the amount of gases dissolved in the water is mainly due to changes of the carbon dioxide content. The carbon dioxide content, however, is the constituent of the gaseous mixture which varies in the most irregular way, such a method is therefore unpracticable.

(iv) **Thermal Conductivity Method:** In this method the gases released from a given sample of the water by bubbling hydrogen through it pass through a thermal conductivity cell - a hot wire cell. By suitable arrangement an electrical signal can be generated which depends on the amount of released gases. The released gases are a function of the amount of gases dissolved in the water. This method has been widely used industrially for measurement of the oxygen content of water. Its application for measuring the total gas content has not

proved satisfactory due to its low accuracy, although the thermal conductivities of O_2 and N_2 are practically equal.

It appears however that a more careful and complete study of this method would lead to an acceptable solution. The great advantage of a method based on thermal conductivity would be the possibility of continuous reading, recording and even controlling the gas content in closed hydraulic circuits.

7. CONCLUSIONS

The result of the present investigation shows that the composition of the dissolved gaseous mixture in a liquid changes not only with the amount of the total dissolved gas content but depends on the previous process history (i.e. aeration or de-aeration). It also depends on the temperature and on the nature and purity of the liquid medium.

For these reasons it is not possible to draw a definite calibration curve which will give the total gas content as a function of the proportions of any of the gaseous constituents in the mixture.

It is not advisable therefore to use any of the indirect methods as a total gas content meter.

So far the only reliable methods for measuring the total gas content are the extraction methods.

Another promising alternative appears to be an improved type of thermal conductivity method.

ACKNOWLEDGEMENT

The work described was undertaken in the Department of Aeronautics and Fluid Mechanics of the University of Glasgow under the guidance of Prof. W.J. Duncan and Dr. A.S. Thom, using equipment loaned by the Mechanical Engineering Research Laboratory. It is published by permission of the Dean of the Faculty of Engineering, University of Glasgow.

Distribution: Groups 4 and 8

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TABLE 1

Values of entrance, exit and partial pressures for saturated water

Gas	a (mg/min cm^2 atm)	b (cm/min)	P (atm)
CO_2	262×10^{-3}	0.152	4.15×10^{-4}
O_2	24.6×10^{-3}	0.538	0.209
N_2	10.8×10^{-3}	0.546	0.790

TABLE 2

Concentrations of gases for different values of γ
(De-aeration starting from φ = 100 per cent)

γ min/cm	exp $(-b_1\gamma)$	exp $(-b_2\gamma)$	exp $(-b_3\gamma)$	C_1 mg/litre	C_2 mg/litre	C_3 mg/litre	$C_o{}^t$ mg/litre	$\frac{C_1}{C_o{}^t}$ %	$\frac{C_2}{C_o{}^t}$ %	$\frac{C_3}{C_o{}^t}$ %	$\frac{C_o{}^t}{C_o{}^o} = \varphi$
0	1	1	1	0.715	9.55	15.60	25.865	2.76	36.90	60.4	100
0.5	0.927	0.764	0.761	0.664	7.29	11.90	19.854	3.34	36.80	59.9	76.6
1.0	0.859	0.584	0.579	0.615	5.57	9.02	15.205	4.04	36.60	59.4	58.7
2.0	0.738	0.341	0.336	0.528	3.25	5.22	9.008	5.87	36.10	58.0	34.7
3.0	0.634	0.199	0.194	0.453	1.90	3.03	5.383	8.40	35.30	56.3	20.8
4.0	0.544	0.116	0.113	0.389	1.10	1.76	3.259	11.95	33.70	54.0	12.6
5.0	0.468	0.0678	0.0652	0.336	0.647	1.01	1.993	16.85	32.40	50.60	7.7
6.0	0.402	0.0396	0.0376	0.287	0.378	0.586	1.251	22.95	30.20	46.9	4.84
7.0	0.345	0.0231	0.0219	0.247	0.220	0.342	0.809	30.60	27.20	42.3	3.12
8.0	0.296	0.0135	0.0126	0.212	0.129	0.197	0.538	39.40	24.00	36.6	2.08
9.0	0.255	0.0079	0.0073	0.183	0.0755	0.114	0.3725	49.10	20.20	30.6	1.44
10.0	0.219	0.0046	0.0043	0.157	0.0440	0.067	0.2680	58.5	16.40	25.0	1.04
12.0	0.161	0.00157	0.00143	0.115	0.0150	0.0223	0.1523	75.5	9.85	14.65	0.59
14.0	0.119	0.00052	0.00048	0.085	0.00495	0.0075	0.0975	87.2	5.08	7.62	0.375
16.0	0.0878	0.00018	0.00016	0.0625	0.00172	0.0025	0.06673	93.7	2.58	3.78	0.257
18.0	0.0648	0.000062	0.000055	0.0462	0.000059	0.000858	0.04765	97.0	1.24	1.76	0.184
20.0	0.0478	0.000020	0.000018	0.0340	0.00019	0.000281	0.03447	98.7	0.50	0.80	0.133

TABLE 3

Concentrations of gases for different values of γ
(Aeration starting from φ = 2.08 per cent)

γ min/cm	C_1 mg/litre	C_2 mg/litre	C_3 mg/litre	$C_o\,t$ mg/litre	φ %	$\frac{C_1}{C_o t}$ %	$\frac{C_2}{C_o t}$ %	$\frac{C_3}{C_o t}$ %
0	0.212	0.129	0.197	0.538	2.08	39.4	24.0	36.6
0.05	0.216	0.388	0.630	1.234	4.77	17.5	31.5	51.0
0.2	0.227	1.110	1.830	3.167	12.20	7.17	35.0	57.8
0.4	0.243	1.970	3.210	5.423	20.90	4.48	36.3	59.3
0.6	0.256	2.760	4.510	7.526	29.00	3.40	36.7	60.0
0.8	0.269	3.440	5.670	9.379	36.20	2.87	36.6	60.4
1.0	0.288	4.060	6.710	11.058	42.60	2.60	36.6	60.5
1.5	0.315	5.350	8.830	14.495	55.80	2.17	36.9	60.8
2.0	0.343	6.350	10.430	17.123	66.00	2.00	37.0	60.9
2.5	0.371	7.100	11.580	19.151	73.80	1.94	37.0	61.0
3.0	0.396	7.670	12.600	20.666	79.60	1.915	37.0	61.0
4.0	0.443	8.460	13.850	22.753	87.50	1.945	37.2	60.8
5.0	0.479	8.900	14.600	23.979	92.50	1.990	37.1	60.8
7.0	0.541	9.330	15.270	25.141	96.80	2.150	37.1	60.7
10.0	0.605	9.500	15.510	25.615	98.80	2.360	37.0	60.6
14.0	0.655	9.530	15.600	25.785	99.30	2.540	37.0	60.6
20.0	0.690	9.550	15.600	25,840	99.50	2.670	36.9	60.5
∞	0.715	9.550	15.600	25.865	100	2.76	36.9	60.4

TABLE 4

Concentrations of gases for different values of γ
(Aeration starting from φ = 0 per cent)

γ min/cm	C_1 mg/litre	C_2 mg/litre	C_3 mg/litre	$C_o t$ mg/litre	φ %	$\frac{C_1}{C_o t}$ %	$\frac{C_2}{C_o t}$ %	$\frac{C_3}{C_o t}$ %
0	0	0	0	0	0	-	-	-
0.05	0.005	0.248	0.420	0.673	2.6	0.745	36.8	62.45
0.1	0.0107	0.497	0.842	1.350	5.2	0.790	36.8	62.30
0.2	0.0214	0.975	1.620	2.616	10.1	0.820	37.3	62.00
0.4	0.0430	1.850	3.060	4.953	19.15	0.87	37.3	61.80
0.6	0.0620	2.635	4.350	7.047	27.20	0.88	37.4	61.70
0.8	0.0820	3.340	5.520	8.942	34.50	0.92	37.4	61.70
1.0	0.101	3.980	6.570	10.651	41.20	0.95	37.4	61.70
1.5	0.146	5.28	8.72	14.146	54.60	1.03	37.3	61.60
2.0	0.187	6.28	10.35	16.817	65.00	1.11	37.3	61.50
2.5	0.226	7.05	11.60	18.876	72.80	1.20	37.3	61.50
3.0	0.262	7.65	12.58	20.492	79.20	1.28	37.2	61.30
4.0	0.326	8.43	13.82	22.575	87.00	1.45	37.3	61.30
5.0	0.380	8.900	14.58	23.860	92.20	1.59	37.2	61.00
7.0	0.468	9.32	15.25	25.038	96.60	1.87	37.2	60.90
10.0	0.559	9.50	15.52	25.579	98.50	2.19	37.1	60.80
14.0	0.630	9.50	15.55	25.680	99.30	2.45	37.0	60.60
20.0	0.680	9.55	15.60	25.830	99.50	2.63	36.9	60.50
∞	0.715	9.55	15.60	25.865	100	2.76	36.9	60.40

TABLE 5

Composition of dissolved gas in water samples from various sources (Ref. 3)

No.	Date Sample was taken	Kind of Water	Temp ^{o}C	$\alpha \times 100$	$\frac{\alpha}{\alpha_s}$	$\frac{\alpha^1}{\alpha_s}$	% by Volume Co_2	% by Volume O_2	% by Volume N_2
1	Dec. 19, 1934	Ordinary Water of the University (immediately after taking the sample).	9.5	2.48	1.06	1.02	4.0	29.7	66.3
2	Feb. 28, 1935	Ordinary Water of City of Sendai (as above)	14.0	2.63	1.24	1.21	1.6	31.4	67.0
3	May 20, 1935	Water in tank of our hydraulic laboratory (as above)	11.8	2.43	1.09	1.02	7.0	30.9	62.1
4	Dec. 13, 1935	Water in tank in our hydraulic laboratory (as above)	9.0	2.49	1.05	0.97	7.5	30.9	61.6
5	Jan. 10, 1935	Distilled Water (one month after taking the sample)	9.8	1.58	0.68	0.68	0.0	32.0	68.0
6	May 26, 1935	Sea Water (at the surface)	16.3	1.95	1.13	0.97	14.4	25.5	60.1
7	May 26, 1935	Sea Water (at a depth of 1.6 m)	16.0	1.91	1.10	0.96	13.1	28.0	58.9
8	May 26, 1935	Sea Water (at a depth of 6.0 m)	11.0	2.06	1.10	0.96	12.0	27.9	60.1
9	-	Water Saturated with air at 15°C (reduced to 0°C, 760 mm)	15.0	2.09	1.00	0.99	1.4	33.3	65.3

α: Total volume of air, reduced to normal conditions (0°C, 760 mm), originally contained in 1 cc of water.

α^1: Same as α but exclusive of Co_2.

α_s: Volume of air, reduced to normal conditions (0°C, 760 mm), contained in 1 cc of air-saturated water at the temperature of the sample water when it was taken (according to Landolt-Börnstein).

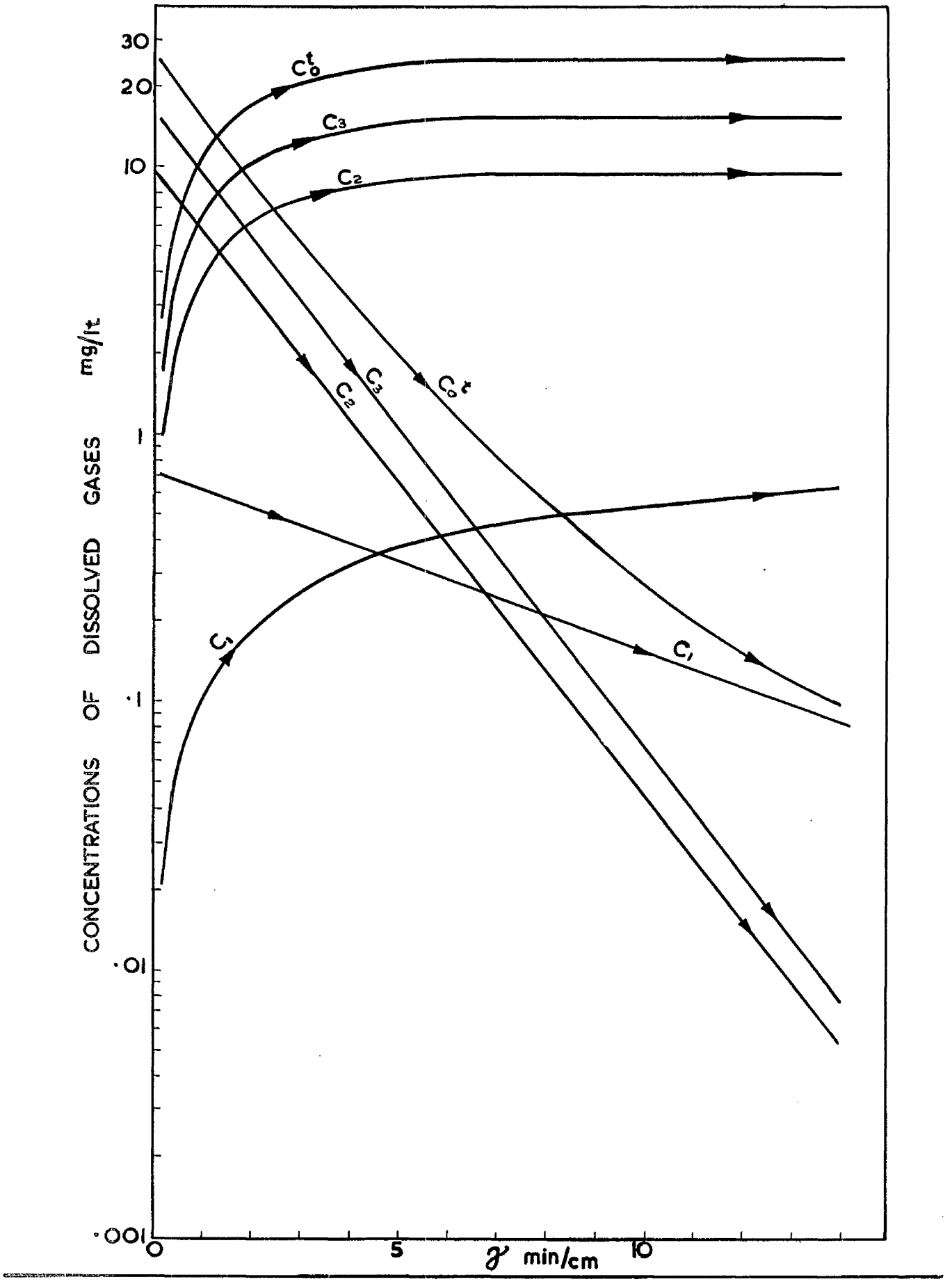

FIG. 1. VARIATION OF γ WITH GAS CONCENTRATION

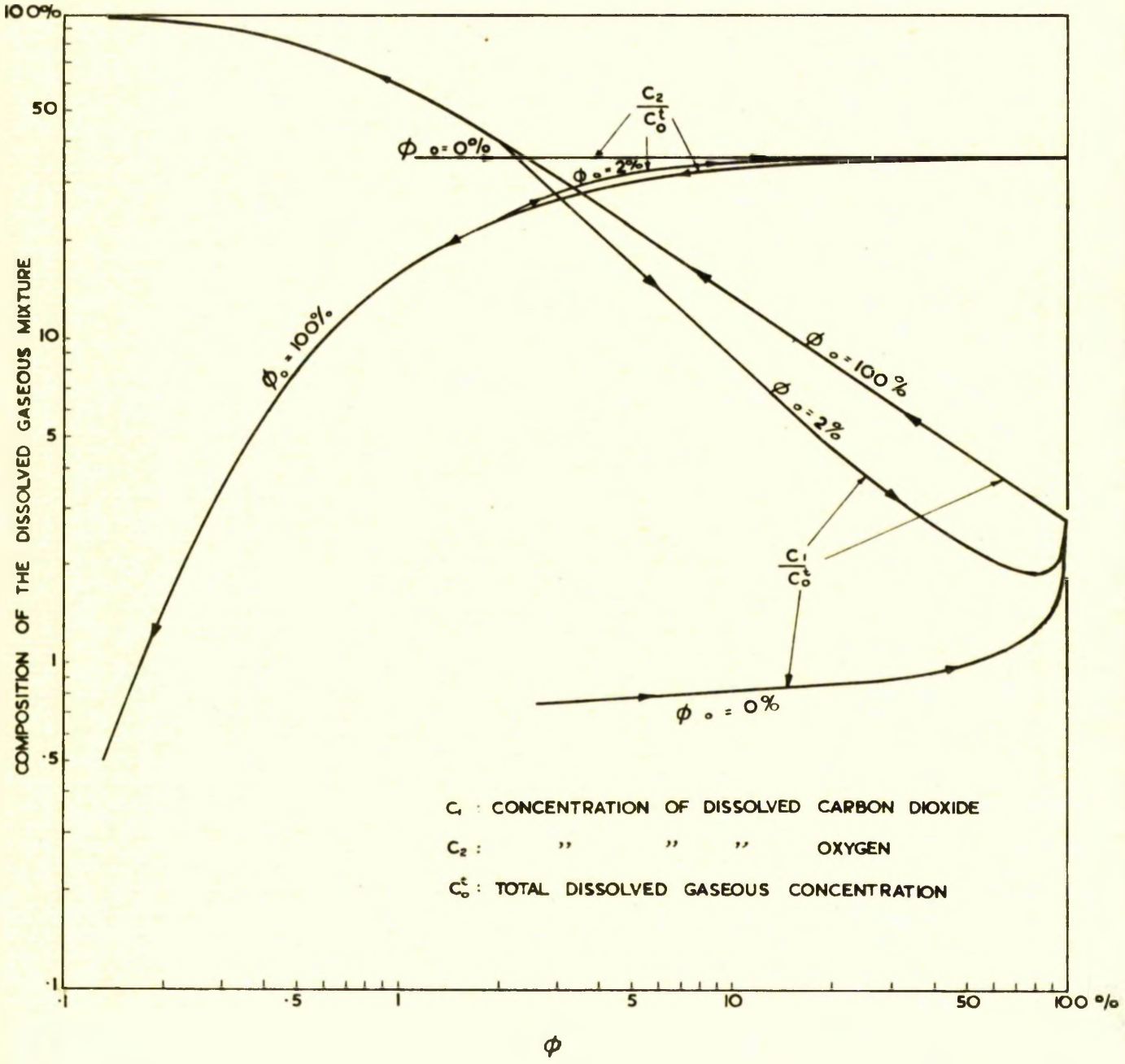

FIG. 2. VARIATION OF DISSOLVED GAS MIXTURE WITH DEGREE OF AERATION

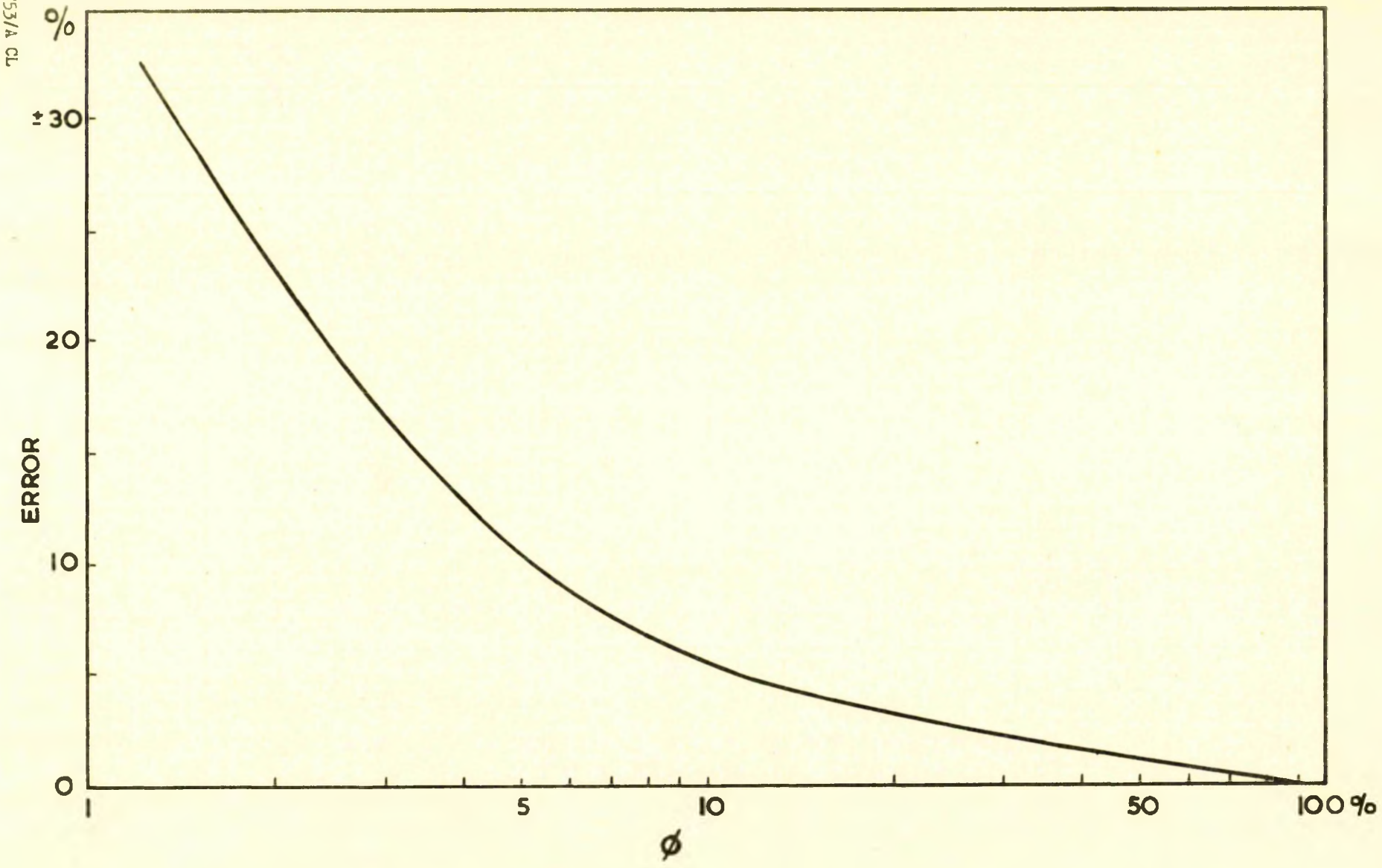

FIG. 3. ERROR IN CALCULATING TOTAL GAS CONTENT FROM MEASUREMENTS OF THE OXYGEN CONTENT

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NEW METHOD FOR MEASURING THE GAS CONTENT OF WATER

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APPENDIX II

April 1958

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DIRECTOR, M.E.R.L., EAST KILBRIDE, GLASGOW

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

MECHANICAL ENGINEERING RESEARCH LABORATORY

NEW METHOD FOR MEASURING THE GAS CONTENT OF WATER

by

E.V. Kanellopoulos, Dipl.Ing.,
M.I.M. and E.E. (Greece)

(University of Glasgow)

S U M M A R Y

A new apparatus for measuring the total gas content of water by extraction is described which is superior to its predecessors in both accuracy and speed of operation. The principle is similar to that of the M.E.R.L. apparatus which itself was an improvement on the Van Slyke apparatus. The alterations include modifications to the spraying chamber and changes to other parts which have resulted in greater ease of handling as well as the above advantages.

A new and more reliable method has been developed for calculating the total gas content of a sample of water. The accuracy using the new apparatus is ± 1 per cent over a very wide range of gas contents.

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CONTENTS (contd.)

NOTE BY M.E.R.L.

Because of the close co-operation of the Fluid Mechanics Division, M.E.R.L. who suggested possible lines of development and loaned some of the apparatus necessary for this research, it was mutually agreed to issue this paper, prior to publication, as a Fluids Report on limited circulation. In so doing it should be made clear that M.E.R.L. have merely exercised a benevolent interest in the progress of the research and that the whole credit for the improved technique and new apparatus is due solely to the author.

1. INTRODUCTION

One of the familiar properties of liquids is their capacity to take up into solution other matter, either solid, liquid or gas.[1]

If a given quantity of gas-free water is exposed in an atmosphere of gas (solute), there is a limited and definite quantity of the gas which may be dissolved in the water at any given temperature and pressure. A solvent which has taken up this limited quantity of the solute (called the solubility) is said to be saturated. If water is saturated under conditions at which the solubility is high (e.g. under high pressure) and the pressure is reduced so that the quantity in solution exceeds the solubility under the new conditions, the water will begin to discharge gas to the gas phase and continue to do so until saturation is reached. A saturated solution is, therefore, a system in equilibrium.

At a given temperature and pressure a solution with solute less than the solubility is called undersaturated while a solution with solute more than the solubility is said to be supersaturated. The attainment of equilibrium between a solvent and a solute from either a supersaturated or an undersaturated condition takes place by a process of diffusion. This process is very slow and it is most effectively accelerated by agitation, spraying, or thorough stirring, thus ensuring intimate contact of solute and solvent.

1.1. Factors which affect solubility of gases in liquids: [2]

The solubility of a gas in a liquid depends on the nature of the gas and the liquid, and also on the temperature and pressure.

Influence of temperature: It is known that gases are readily expelled from solution by boiling. Generally, increase of temperature will result in decrease of solubility.

Influence of pressure: As is to be expected from kinetic considerations, compression of the gas will tend to increase its solubility.

1.2. Methods of expressing solubility:

Among different methods of expressing the solubility of gases in liquids[3] the following two are mostly used.

(i) **Bunsen absorption coefficient** α: This is defined as the volume of gas, reduced to $0^{\circ}C$ and 760 mm pressure of mercury dissolved by unit volume of the liquid at the temperature of the experiments under a partial pressure of the gas of 760 mm of mercury.

If v_0 is the volume of gas dissolved, reduced to N.T.P., V is the volume of liquid and p is the partial pressure of the gas in mm of mercury, then the absorption coefficient of the gas obeying Henry's Law is given by

$$\alpha = \frac{v_0\ 760}{V\ p} \qquad \ldots\ldots(1)$$

(ii) **Ostwald coefficient of solubility** λ: This is defined as the volume of gas, measured under the temperature and pressure at which the gas dissolves, taken up by unit volume of the liquid.

If v is the actual volume of gas dissolved at absolute temperature T and under partial pressure p, by volume V of liquid

$$\lambda = \frac{v}{V} \tag{2}$$

If the gas, however, obeys the law of perfect gases

$$v = v_0 \cdot \frac{T}{273} \cdot \frac{760}{p} \tag{3}$$

From equations (1), (2) and (3), the relationship between the two coefficients is:-

$$\lambda = \alpha \frac{T}{273} \tag{4}$$

1.8. Laws relating to solubility of gases in liquids:

(i) **Henry's Law:**

W. Henry expressed his law as follows[4]: "Under equal circumstances of temperature, water takes up, in all cases, the same volume of condensed gas as of gas under ordinary pressure". From Henry's law it follows that the Ostwald coefficient of solubility (λ) at a given temperature should be independent of pressure. Henry's Law holds fairly accurately for gases of low or moderate solubilities (e.g. O_2, N_2, H_2, CO_2) and low and moderate pressures. Very soluble gases at all pressures and all gases at high pressures show considerable divergence from Henry's law.

(ii) **Mixture of two or more gases. Henry-Dalton's Law:**

If two or more gases occupy the same volume then each component exerts a pressure - partial pressure - equal to the pressure which it would exert if it occupied this volume alone.

In a mixture of two or more gases in contact with some liquid, each gas obeying Henry's law, their solubilities will be proportional to their corresponding partial pressures.[5]

Let the gases in contact with a liquid be G_1, G_2---G_n with corresponding absorption coefficients α_1, α_2---α_n for a given temperature and let the partial pressures be p_1, p_2---p_n. If v_{o_1}, v_{o_2}---v_{o_n} are the corresponding volumes of these gases reduced to N.T.P. which are dissolved by volume V of liquid, then from equation (1)

$$\left.\begin{aligned} v_{o_1} &= \frac{\alpha_1 V p_1}{760} \\ v_{o_2} &= \frac{\alpha_2 V p_2}{760} \\ &\cdots\cdots\cdots \\ v_{o_n} &= \frac{\alpha_n V p_n}{760} \end{aligned}\right\} \quad \cdots\cdots\cdots (5)$$

The unit volume of the dissolved gaseous mixture will contain fractions

$$\left.\begin{aligned} u_1 &= \frac{\alpha_1 p_1}{\alpha_1 p_1 + \alpha_2 p_2 + \cdots \alpha_n p_n} \\ u_2 &= \frac{\alpha_2 p_2}{\alpha_1 p_1 + \alpha_2 p_2 + \cdots \alpha_n p_n} \\ &\cdots\cdots\cdots\cdots\cdots\cdots \\ u_n &= \frac{\alpha_n p_n}{\alpha_1 p_1 + \alpha_2 p_2 + \cdots \alpha_n p_n} \end{aligned}\right\} \quad \cdots\cdots\cdots\cdots (6)$$

of the corresponding gases G_1, G_2 $\cdots G_n$.

(iii) **Just's conclusion:**

The ratio of the solubilities of two gases in liquid is independent of the liquid.

(iv) **Law of perfect gases:**

$$\frac{p\,v}{T} = \frac{p_1\,v_1}{T_1} \quad \cdots\cdots\cdots\cdots (7)$$

Henry's law is strictly applicable only to ideal systems, and any departure from ideal behaviour of the gas will result in deviations from Henry's law. Such deviations are, therefore, to be expected at low temperatures and high pressures.

1.4. Influence on the cavitation characteristics of the amount of gases dissolved in water

The amount of gases dissolved in water influences the density, viscosity, compressibility, surface tension and tensile strength of the water. It also affects the inception and development of cavitation and subsequent erosion. The old assumption for the inception of cavitation was that the inception took place in a hydraulic circuit as soon as the local pressure was reduced to the vapour pressure of the water corresponding to the temperature of the experiments. It has now been proved that there is no definite value for the critical inception pressure. This critical pressure may be greater or smaller than the corresponding vapour pressure; it may even be negative and its magnitude depends on different factors, among which the most important are the gas nuclei content and the dissolved gas content.

Recent opinion is that inception of cavitation is due to the increase in size of microscopic gas nuclei (of the order 10^{-3}- 10^{-5} cm) up to visible size. The dissolved gas content influences the size and the number of the gas nuclei. In general, the critical pressures for the inception of cavitation are reduced as the dissolved gas content is reduced, with apparent tension in de-aerated water.

In addition the dissolved gas content influences the collapse of the cavitation bubbles. In de-aerated water the cavities are filled with water vapour. On entering a region of high pressure, due to the

condensation of the water vapour the bubbles collapse suddenly with instantaneous reduction of their volume practically to zero. In water with a high gas content, however, the cavities are partly filled with water vapour and gas. During the collapse, the water vapour condenses suddenly but instantaneous dissolving of the gas is not possible due to the relatively slow process of diffusion. The gas content thus acts to cushion the shock of the collapsing cavitation bubble. This and the fact that the dissolved gas content increases the compressibility of the water results in reduction of the intensity of the cavitation damage in the case of high gas contents.

1.5. Methods for determination of the solubility of gases in liquids [6]

There are two basic methods for the determination of the solubility of gases in liquids:

(i) Chemical methods;

(ii) Physical methods.

(i) **Chemical methods:** The chemical methods depend on specific chemical properties of the gas and thus can be used with only a limited number of gases. Winkler developed[7] a chemical method for the determination of oxygen in solution. This method has been of value both in the analysis of natural waters and in solubility measurements.

(ii) **Physical methods:** The physical methods are divided in two: the saturation and the extraction methods. In both the physical methods it is necessary to prepare a gas-free sample of liquid. The usual method of de-aeration of a liquid is boiling and subsequent cooling under vacuum.

(a) **Saturation Method:** A quantity of the gas whose solubility in a liquid is required, is introduced into a special vessel and the pressure, volume and temperature are measured. A given quantity of gas-free liquid is introduced into another vessel. Communication is now made between the two vessels and the whole apparatus is thoroughly shaken for sufficient time until it is observed that saturation has been attained. The pressure volume and temperature of the remaining gas is now measured. The difference between the initial and final quantity represents the amount of gas that has dissolved in a given quantity of the liquid. At different times different kinds of apparatus have been invented based on the saturation method.[2, 5, 8, 9]

(b) **Extraction method:** In this method for the determination of the solubility, a given quantity of saturated liquid is introduced into the apparatus and shaken under vacuum for sufficient time. The pressure, volume and temperature of the released gas

are then determined. Applications of this method are the Van Slyke apparatus, the M.E.R.L. apparatus and the modified apparatus described in this report.

Van Slyke apparatus: [10, 11] The principle of operation of this apparatus is as follows. A measured volume of water is subjected to a Torricellian vacuum and the water is agitated, by shaking the sample container, to facilitate the escape of the gases, Fig. 1. When sufficient time has elapsed to enable the gases to escape into the vacuum, the gases are constrained to occupy a known volume by adjusting the level of a mercury reservoir. The partial pressure of the gases is measured by the manometer connected to the apparatus and the gaseous volume, referred to N.T.P., is obtained by application of the perfect gas laws.

M.E.R.L. apparatus: [12, 13, 14] The principle is similar to that of the Van Slyke method but the water is agitated by repeatedly spraying the sample into a vacuum, using the mercury reservoir to produce the pumping pressure, Fig. 2. After the dissolved gases have escaped the procedure is similar to that described above.

Modified apparatus: The principle of operation is similar to that of the M.E.R.L. apparatus. The differences are in the shape of the spraying chamber and other parts of the apparatus, Fig. 3, and in the method of calculating the gas content. The present modified apparatus has been developed as part of a research programme and is needed for measuring the air content of the water in a cavitation circuit. In this context air content will be taken to mean, the *total air content*, i.e. the sum of dissolved air, the air nuclei and the entrained air. It should be noted that, in the extraction method, the total air content is released, not only the dissolved air content.

The present apparatus is an improvement on the M.E.R.L. method as far as the accuracy, operating time and facilities of handling are concerned.

2. THEORETICAL ANALYSIS

2.1. General

The modified apparatus is shown in Figs. 3 and 4. A sample of 10 c.c. of water is agitated by repeatedly spraying the sample into a Torricellian vacuum, using the mercury reservoir to produce the pumping pressure. After a certain number of sprays the released gases are constrained to occupy a known volume (1 cm^3) by adjusting the level of the mercury reservoir. The pressure of the gaseous mixture is measured by the manometer connected to the apparatus. The released gases are then expelled, the level of the water is brought back to the 1 c.c. mark and the new reading of the manometer is taken.

From these two readings the partial pressure of the released gases is calculated.

The number of sprays which is to be used in the present method is that number after which more sprays show no distinct increase in the partial pressure of the released gases. It is shown in Fig. 8 that 12 sprays are sufficient for that purpose.

The fact that after say 12 sprays there is no distinct increase in the partial pressure of the released gases does not mean that the sample is completely degassed. There is a limit to the degree of degassing due to the pressure which the released gases exert in the space above the water. This limit can be calculated by application of Henry's law. The actual amount of gases which remains in solution after the first set of sprays was found as follows. After expelling the gases released by the first set of sprays the sample was subjected to a second set of sprays and again to a third set of sprays.

The results of the experiments show that the amount of gases which remains in solution after the first set of sprays is far greater than the amount of gases which is calculated by the Henry's law.

2.2. Calculations

In the M.E.R.L. method the gas content of a sample of water is expressed by the formula:

$$p_o = x_1 - x_2 \qquad (8)$$

where

x_1 is the manometer reading in mm. of mercury after constraining the released gases in 1 cm^3 volume, and

x_2 is the manometer reading in mm of mercury after expelling the released gases and bringing the level of water back to 1 cm^3 mark. The above formula is correct (a) if the manometer attached to the apparatus behaves as barometer, (b) if there is no loss of water during the expelling of the gases, and (c) if the sample of the water is completely degassed after the spraying. None of these assumptions, however, is fulfilled.

If x indicates the height of the manometric column above the zero of the manometric scale, x^1 the height of the mercury in the spraying chamber limb above the same zero, h the elevation of the 1 cm^3 mark above the zero level (Fig. 3), p_a the pressure in the gaseous space of the manometer corresponding to x, p_b the partial pressure of the leakages in the spraying chamber limb reduced to 1 cm^3 volume, p_v the vapour pressure, γ_w the specific gravity of the water, γ_h the specific gravity of the mercury and if suffixes 1 and 2 are used for the conditions after constraining the released gases in 1 cm^3 volume and after expelling the released gases, then the following relationships can be obtained:

$$p + p_{b_1} + p_v + (h - x_1^1)\frac{\gamma_w}{\gamma_h} = p_{a_1} + (x_1 - x_1^1)$$

and

$$p_{b_2} + p_v + (h - x_2^1)\frac{\gamma_w}{\gamma_h} = p_{a_2} + (x_2 - x_2^1)$$

from which

$$p = (x_1 - x_2) + (p_{a_1} - p_{a_2}) + (p_{b_2} - p_{b_1}) + \frac{x_2^1 - x_1^1}{\gamma_h}(\gamma_h - \gamma_w) \quad \ldots\ldots (9)$$

and using equation (8),

$$p = p_o + (p_{a_1} - p_{a_2}) + (p_{b_2} - p_{b_1}) + \frac{x_2^1 - x_1^1}{\gamma_h}(\gamma_h - \gamma_w) \quad \ldots\ldots (10)$$

where p is the correct value for the pressure of the released gases constrained in 1 cm^3 volume.

If Σz represents the amount of gases still remaining in solution after the spraying, expressed as the pressure, in mm of mercury, which these gases would exert if released and occupied a volume of 1 cm^3, the total gas content of the sample is

$$p_{th}^* = p_o + (p_{a_1} - p_{a_2}) + (p_{b_2} - p_{b_1}) + \left[\frac{x_2^1 - x_1^1}{\gamma_h}\right](\gamma_h - \gamma_w) + \Sigma z \quad \ldots\ldots (11)$$

(i) **Interpretation of formula (11)**

Each of the terms $(p_{a_1} - p_{a_2})$, $(p_{b_1} - p_{b_2})$, $\frac{x_2^1 - x_1^1}{\gamma_h}(\gamma_h - \gamma_w)$, Σz can be considered separately.

(a) $(p_{a_1} - p_{a_2})$

If there is some leakage in the manometer tube then the entrained air will obey the perfect gas laws. The pressure p_a for a given x will then be

$$p_a \{V_o + (x_o - x)u_o\} = C.T. \quad \ldots\ldots (12)$$

where

x_o is an arbitrary maximum value of x (constant of the apparatus)
V_o is the volume of the manometer tube above x_o.
u_o is the volume per mm length of the tube
C is proportional to the amount of entrained air. (C is constant if the leakage into the tube does not continue.)
and T is the absolute temperature of the experiments.

Let both C and T be constant. Then

$$CT = C_1 = \text{constant} \quad \ldots\ldots (13)$$

Because x_1 is always greater than x_2 it follows that $p_{a_1} > p_{a_2}$

From equations (12) and (13)

$$p_{a_1} = \frac{C_1}{k - u_o x_1}$$

$$p_{a_2} = \frac{C_1}{k - u_o x_2}$$

where $k = V_o + x_o u_o$

and hence

$$p_{a_1} - p_{a_2} = C_1 u_o \quad \frac{x_1 - x_2}{(k - u_o x_1)(k - u_o x_2)}$$

or

$$\frac{p_{a_1} - p_{a_2}}{x_1 - x_2} = \frac{p_{a_1} - p_{a_2}}{p_o} = \frac{C_1 u_o}{(k - u_o x_1)(k - u_o x_2)} \qquad (14)$$

Because x_2 is nearly constant (as found by experiments) it follows from equation (14) that $\frac{p_{a_1} - p_{a_2}}{p_o}$ increases as x_1 increases; that is the error obtained by neglecting the term $(p_{a_1} - p_{a_2})$ is greater for higher gas contents.

(b) $(p_{b_2} - p_{b_1})$

It is not possible to calculate this term. All that can be said is that this difference is small and is always positive. In fact p_{b_1} represents the pressure of the leakage while p_{b_2} consists of the same plus the pressure of a very small amount of gases which is released from the sample during the period of taking the second reading of the manometer.

(c) $\frac{x_2^1 - x_1^1}{\gamma_h} (\gamma_h - \gamma_w)$

During the expelling of the released gases some loss of the water sample occurs, the magnitude of which is not under control. In order to ensure complete expelling of the gases it is advisable to have a small loss of the water sample.

This has a result $x_2^1 > x_1^1$

Therefore, the term $\frac{x_2^1 - x_1^1}{\gamma_h} (\gamma_h - \gamma_w)$ is always positive.

Now $\gamma_h \simeq 13.6$ and $\gamma_w = 1$ and hence

$$\frac{x_2^1 - x_1^1}{\gamma_h} (\gamma_h - \gamma_w) \simeq 0.927 \ (x_2^1 - x_1^1) \qquad (15)$$

$(x_2^1 - x_1^1)$ is independent of $(x_2 - x_1)$ and so the error introduced by neglecting the term $\frac{x_2^1 - x_1^1}{\gamma_h}(\gamma_h - \gamma_w)$ increases for samples of water with low gas contents.

(d) Σz

This term includes the amount of gases with which the water sample is saturated under the conditions existing at the end of the last spray and the amount of gases which are redissolved during the compression of the released gases in order to take the first reading of the manometer. An attempt to evaluate this term for the case of water samples which have been used in the experiments described later, can be made.

The water used in these experiments was tap water saturated with air under atmospheric conditions. The temperature of the experiments was about 20°C.

The mean composition of the atmospheric air is taken as:

O_2 - 20.9512% of volume of air
N_2 - 79.0073% " " " "
CO_2 - 0.0415% " " " "

For 20°C temperature, the absorption coefficient can be determined from the International Critical Tables[3] which give $K.10^{-6}$ values for oxygen, nitrogen and carbon dioxide as 30.4, 59, and 1.07 respectively.

$$K = \frac{17\ 032\ 400d}{M\alpha} + p_A \qquad (16)$$

where

d = density of solvent
M = molecular weight of liquid
p_A = partial pressure of gas in mm of mercury
and α = Bunsen absorption coefficient.

For water d = 1 g/cm^3 and M = 18. Substituting the values of d, M, p_A and K into equation (16) the following values of α are obtained.

O_2 : 0.0310 N_2 : 0.0160 CO_2 : 0.8820

The composition of the gaseous mixture in water saturated with atmospheric air at 20°C will be given by equation (6).

u_{O_2} = 33.28%
u_{N_2} = 64.85%
u_{CO_2} = 1.87%

If the whole amount of air which is dissolved in the 10 cm^3 sample of water were released and constrained in 1 cm^3 volume its pressure would be about 170 mm Hg. The partial pressure of the gaseous components would be:

$$170 \cdot \frac{33.28}{100} = 56.576 \text{ mm Hg.}$$

$$170 \cdot \frac{64.85}{100} = 110.245 \text{ mm Hg.}$$

$$170 \cdot \frac{1.87}{100} = 3.179 \text{ mm Hg.}$$

According to Henry's Law the sample of the water will not be gas free at the end of the first set of sprays. In order to calculate the amount of gases which remains in the sample after the first set of sprays it can be assumed that the water is saturated with the different gases under the existing partial pressures at the moment when the last spray is completed. The volume of the gas space at this moment is about 42 cm^3 (Fig. 6). Now the amount of gases which remains in solution after the first set of sprays can be calculated as follows:

Carbon dioxide

Under the stated conditions the pressure of the CO_2 constrained in 1 cm^3 volume initially dissolved in the sample of water is 3.179 mm Hg. For 42 cm^3 volume the pressure of CO_2 will be

$$\frac{3.179}{42} .$$

During the spraying process part of this amount will be released. If Z'_{CO_2} denotes the amount of CO_2 which remains in solution expressed in mm of mercury for 42 cm^3 volume the corresponding pressure of the released CO_2 will be

$$p'_{CO_2} = \frac{3.179}{42} - Z'_{CO_2}$$

We know that under 760 x $\frac{0.0415}{100}$ = 0.320 mm Hg partial pressure of CO_2 the sample of water has dissolved an amount of CO_2 which under 42 cm^3 volume will be $\frac{3.179}{42}$ mm Hg.

By applying Henry's Law

$$Z'_{CO_2} = \frac{3.179}{42}\left(\frac{\frac{3.179}{42} - Z'_{CO_2}}{0.32}\right)$$

from which

$$Z'_{CO_2} = 0.0143 \text{ mm Hg.}$$

Reduced to 1 cm^3 volume,

$$Z_{CO_2} = 42Z'_{CO_2} = 0.600 \text{ mm Hg}$$

and the partial pressure of the released CO_2 for 1 cm^3 volume will be

$$p_{CO_2} = 3.179 - 0.600 = 2.579 \text{ mm Hg.}$$

Oxygen

Following a similar procedure the amount of O_2 still in solution in the sample expressed in mm Hg for 1 cm^3 volume was found to be $Z_{O_2} = 0.472$ mm Hg

and the partial pressure of the released O_2 for 1 cm^3 volume to be

$$p_{O_2} = 56.576-0.472 = 56.104 \text{ mm Hg.}$$

Nitrogen

Similarly

$$Z_{N_2} = 0.475 \text{ mm Hg.}$$

and

$$p_{N_2} = 110.245-0.475 = 109.770 \text{ mm Hg.}$$

So the total amount of gases which according to Henry's Law remains still in solution expressed in mm Hg under 1 cm^3 volume is $Z_g = Z_{CO_2} + Z_{O_2} + Z_{N_2} = 0.600+0.472+0.475 = 1.547$ mm Hg and the amount of gases released is

$$p_g = p_{CO_2} + p_{O_2} + p_{N_2} = 2.579 + 56.104 + 109.770 = 168.453$$

Z_g expressed as percentage of p_g is

$$Z_g = 0.92\% \, p_g.$$

(ii) **Calculation of the amount of gases which redissolved in the sample during the period of compression for taking the reading of the manometer.**

The net rate at which a gas enters a liquid for any conditions of area exposed, depth of liquid or degree of saturation, provided that the liquid is kept uniformly mixed*, is: (15, 16, 17, 18, 19)

$$\frac{dm}{d\tau} = (\alpha P - bc)A \qquad (17)$$

---

*FOOTNOTE: The above formula is not strictly applicable in this case because the mixing of the water sample is not very uniform. However, an idea of the order of magnitude of the amount of gases which are redissolved in the sample can be obtained.

where

dm is the amount entering through an area A in the time $d\tau$

P is partial pressure of the gas

c is the concentration of the gas in the liquid

a is entrance coefficient

and b is exit coefficient.

The coefficients a and b are given in tables[15] and both depend on the nature of the gas and the temperature. a is given in units mg/min cm^2 atm, while b is in cm/min. The concentration can be expressed as $c = \frac{m}{V_w}$ ..... (18)

where m is the total amount of gas in the water at any instant and V_w is the volume of the water sample.

Equation (17) holds as it is, if m is expressed in mg, τ in min, P in atmospheres, c in mg/cm^3 and A in cm^2.

It is convenient for the following calculations to express some of the terms of equation (17) in suitable units.

The mass of a gas is given by [20]

$$m' = 5.44 \times 10^{-8}\ MZ'v \text{ grammes at } 20^{\circ}C \quad \ldots\ldots (19)$$

where

M = molecular weight of the gas

Z' = pressure in μ Hg.

and v = volume in litres.

If Z is the pressure in mm Hg which the amount of gas in the water sample at any moment would exert in 1 cm^3 volume and m is in mg, then:

$$m = 5.44 \times 10^{-5}\ MZ$$

If P is expressed in mm Hg (p), τ in sec. (t) and $c = \frac{m}{V_w}$ where $V_w = 10$ cm^3 the equation (17) can be written:

$$5.44 \times 10^{-5}\, M \frac{dZ}{dt} = \left(\frac{\alpha}{760}\,\frac{1}{60}\,p - \frac{b}{60}\,\frac{5.44 \times 10^{-5} MZ}{10}\right) A$$

or
$$\frac{dZ}{dt} = \left(\frac{ap}{760 \times 60 \times 5.44 \times 10^{-5} M} - \frac{b}{600}\,Z\right) A$$

from which
$$\frac{dZ}{dt} = \left(0.404\,\frac{ap}{M} - \frac{1.666}{10^3} \times b.Z\right) A \quad \ldots\ldots (20)$$

At any moment if V is the volume of the gas space above the liquid surface, then

$$pV + Z = q = \text{constant}$$

or
$$p = \frac{q - Z}{V} \quad \ldots\ldots (21)$$

If the value of p is substituted into equation (20)

$$\frac{dZ}{dt} = \left(0.404\ \frac{\alpha}{M}\left(\frac{q - Z}{V}\right) - 1.666 \times 10^{-3}\ bZ\right) A$$

or

$$\frac{dZ}{dt} = \left\{0.404\ \frac{\alpha q}{M} - \left(0.404\ \frac{\alpha}{M} + 1.666.qp^{-3}Vb\right)Z\right\}\frac{A}{V} \qquad (22)$$

	M	q (mm Hg)	α (mg/min cm^2 atm)	b (cm/min)
CO_2	44	3.179	262.0×10^{-3}	0.152
O_2	32	56.576	24.6×10^{-3}	0.538
N_2	28	110.245	10.8×10^{-3}	0.546

If these values are used, then:

for CO_2

$$\frac{dZ}{dt} = 10^{-3}\left\{7.65 - (2.4 + 0.253V)Z\right\}\frac{A}{V} \qquad (23)$$

for O_2

$$\frac{dZ}{dt} = 10^{-3}\left\{17.6 - (0.31 + 0.895V)Z\right\}\frac{A}{V} \qquad (24)$$

and for N_2

$$\frac{dZ}{dt} = 10^{-3}\left\{17.3 - (0.157 + 0.91V)Z\right\}\frac{A}{V} \qquad (25)$$

In the above equations, A and V are both functions of time t. Due to the irregular shape of the spraying chamber the functions $A = A(t)$ and $V = V(t)$ cannot be expressed mathematically. In Fig. 6 the values of A, V, t are plotted against x, where x is the elevation of any cross section of the apparatus above the zero of the manometer scale.

Numerical solution of the differential equations (23), (24) and (25) with A and V taken from Fig. 6, gives the following values for the amount of gases in solution at the time of taking the first reading of the manometer:

$$Z_{CO_2} = 0.640 \text{ mm Hg.}$$

$$Z_{O_2} = 0.588 \text{ "}$$

$$Z_{N_2} = 0.590 \text{ "}$$

$$Z_{CO_2} + Z_{O_2} + Z_{N_2} = 1.818 \text{ mm Hg}$$

The amount of the gases released is 170 - 1.818 = 168.182 mm Hg. The error, therefore, by neglecting the term Δz is

$$\frac{1.818}{168.182} 100 = 1.09\%$$

(iii) **Second set of sprays**

The actual amount of gases remaining in solution after the first set of sprays can be found experimentally by a second and third set of sprays. Let x_3 be the reading of the manometer and x_3^1 be the level of the mercury in the spraying chamber limb, after the gases released from the second set of sprays have been constrained, in 1 cm^3 volume. Then

$$\Delta p_2^1 = (x_3 - x_2) + \frac{x_2^1 - x_3^1}{\gamma_h} (\gamma_h - \gamma_w) \quad \ldots\ldots (26)$$

where Δp_2^1 is the partial pressure of the released gases. In the above formula, similar to equation (9), the term $(p_{a_3} - p_{a_2})$ is neglected as being very small. The gases expressed as Δp_2^1 are released from a volume of water $V_2 < 10$ cm^3. The correct value for 10 cm^3 sample of water is

$$\Delta p_2 = \Delta p_2^1 \frac{10}{V_2} \quad \ldots\ldots (27)$$

(iv) **Third set of sprays**

If x_4 and x_4^1 are the levels of mercury after expelling the gases released from the second set of sprays and x_5 and x_5^1 are the levels of mercury after the third set of sprays, then according to equation (26) and (27) we get

$$\Delta p_3^1 = (x_5 - x_4) + \frac{x_4^1 - x_5^1}{\gamma_h} (\gamma_h - \gamma_w) \quad \ldots\ldots (26a)$$

and

$$\Delta p_3 = \Delta p_3^1 \frac{10}{V_3} \quad \ldots\ldots (27a)$$

(v) **Gas content of the sample**

The total gas content of the sample expressed as the pressure in mm of mercury which it would exert if completely released and constrained in 1 cm^3 volume is obtained from equation (11), if $(p_{a_1} - p_{a_2})$ is taken from actual calibration curves and if $(\Delta p_2 + \Delta p_3)$ replaces the term Δz. Therefore

$$p^* = p_o + (p_{a_1} - p_{a_2}) + 0.927 (x_2^1 - x_1^1) + (\Delta p_2 - \Delta p_3) \quad \ldots\ldots (28)$$

If now t is the temperature of the experiments in ^oC and V* is the volume of the gases referred to N.T.P., then by applying the perfect gas law, (equation (7)),

$$\frac{p^* V}{273 + t} = \frac{760\ V^*}{273}$$

where

$$V = 1 \text{ cm}^3$$

and

$$V^* = \frac{273\ p^*}{(273 + t)\ 760} \text{ cm}^3 \text{ gas/10 cm}^3 \text{ water}$$

$$V^* = p^* \frac{35.92}{273 + t} \text{ cm}^3 \text{ gas/litre water} \qquad (29)$$

2.3. Analysis of errors

The errors which may occur in the present method can be divided in two parts:

(i) Errors which take place in the manometer limb, and

(ii) Errors which take place in the spraying chamber.

(i) Manometer limb

(a) A systematic error will occur due to the inaccuracy of the scale and of reading. This is of the order of ±0.05 mm for each reading.

(b) Another systematic error is introduced from the calibration of the manometer, e.g. for plotting the curve $p_a = f(x)$. This contains the above error (a) plus the error in taking the level of mercury in the mercury reservoir. This latter is due to the thread of the rack and pinion. If t is the pitch of the thread then this error will be $\pm\frac{t}{2}$.

For high gas contents the above errors, (a) and (b), are negligible but they become quite appreciable for very low air contents.

(c) The calibration curve $p_a = f(x)$ is plotted for CT = constant (equation (13)). If the temperature of the experiments changes and/or C changes (C will always remain constant or will increase) then p_a will change and of course $(p_{a_1} - p_{a_2})$. It has been observed from the experiments that this change in C takes place during the first two or three tests after the stop-cock on the top of the manometer has been regreased and the trapped air expelled. After that C remains nearly constant.

(ii) Spraying chamber limb

(a) An error is introduced by neglecting the term $(p_{b_2} - p_{b_1})$ in equation (10). In order to reduce this error the same procedure is always followed. Having initially made sure that the polythene tubes connected to the apparatus are filled with water, the cock A (Fig. 3) is opened and by raising the mercury reservoir the mercury is allowed to rise first into the glass tube over the cock. Next the reservoir is lowered until the mercury occupies the bottom of the bore of the cock. Then the cock is turned and the water left to run. After

this the cock is again opened and by lowering the reservoir the sample is very slowly introduced into the volumetric tube. This procedure is similar to the process of expelling the gases and it is hoped that the difference $(p_{b_2} - p_{b_1})$ will therefore be very small.

(b) Another error is due to inaccuracy in taking the 10 cm^3 of water sample.

(c) An error is introduced by the method of spraying, which affects the degree of de-aeration of the sample. The extraction of gases from the sample depends on

The number of sprays;

The total time of spraying;

The method of spraying.

Referring to the method of spraying, it must be pointed out that the velocity of the water jet as well as the size of the water-gas interface depends on the pressure under which the spraying process takes place. Consequently in the present method, by providing the stopper S_3 (Fig. 3) the same spraying pressure is always used. Extraction of gases can now take place always under the same standard condition.

(d) Finally, an error is introduced when the released gases are constrained in 1 cm^3 volume. This error arises from two sources: firstly, inaccuracy in bringing the level of water to the 1 cm^3 mark, and secondly, due to the contamination of the walls of the glass tube, some water from the condensation of water vapour remains on the walls. The actual volume of gases is thus less than 1 cm^3. In order to reduce the second error the gases are compressed by raising the mercury reservoir and then slowly bringing the water level to the 1 cm^3 mark.

During the second and third set of sprays the same errors are introduced but these - except the systematic errors - are negligible.

From experiments on samples of water with the same air content (tap water which remained in a large tank for several days) it was found that the present method was accurate to within ±1%.

3. DETAILS OF THE APPARATUS

3.1. General Description

Referring to Fig. 3, *A* is a three-way cock with which the liquid to be tested may be drawn into the volumetric "tube" from I or expelled through II. Alternatively the liquid may flow through directly from I to II. The volumetric tube has been calibrated for 1, 2, 10 and 11 cm^3. *S* is the spraying chamber of the apparatus, Fig. 5. The purpose of this shape of the spraying chamber is to give the spraying water the opportunity to stay more time in the form of a thin layer under the low pressure thus reducing the number of sprays necessary.

B is a T-bore cock and is used for spraying the water through the two very fine bore spraying nozzles N_1 and N_2 and it connects S to the bulb X. The bore of the cock B which connects S to X is made relatively large in order to reduce the time which the sample needs to return to the bulb X after each spray. Cock C has a small and a large bore. The large bore is used for spraying the sample while the small one is used to draw the sample of the water into the apparatus and to adjust the level of the water to the 1 cm^3 mark. The manometer tube has a $\frac{1}{4}$ inch bore and on the top is blown the bulb Y with a volume of about 5 cm^3. The purpose of this bulb is to reduce the differences $(p_{a_1} - p_{a_2})$. From equation (14) it can be seen that $\frac{p_{a_1} - p_{a_2}}{x_1 - x_2}$ decreases as k increases in comparison with $u_o x_1$ and $u_o x_2$. Now since k equals $(V_o + x_o u_o)$ the only way of increasing k is to make V_o sufficiently large. D is a stop-cock and is opened only to expel any air which may have leaked into the manometer. The manometer limb is made higher than the spraying chamber limb in order to be able to take the readings of the pressure of the released gases constrained in 1 cm^3 volume for very high gas contents.

M_1 and M_2 are rubber-mercury sealings and connect the U of the apparatus to the spraying chamber limb and manometer tube correspondingly. K_1 and K_2 are two scales with divisions in mm and with their zeros in the same horizontal plane. K_1 carries the verniers W_1 and W_2 and K_2 the vernier W_3. The mercury reservoir R slides vertically on the rails S' and S'' when pulled by the string S_1 which passes over the pulley P. S_2 is a stopper for the lowest position of the reservoir R and is arranged so that the lowest level of the mercury in the spraying chamber limb will always be in the bulb X for any barometric pressure. If the reservoir R were free to move below the above level then leakages may take place through the rubber-mercury sealing M_1.

S_3 is a stopper which is used during the period of spraying. This stopper serves two purposes, (a) to give to each spray the same pumping pressure and (b) to prevent the top of the mercury column reaching the cock D. Without this stopper, due to the sudden raising of the reservoir it is impossible to avoid the impinging of the mercury column against the cock D. This repeated many times would damage the cock.

K_3 is a scale which is moved vertically by means of a rack-pinion system. On its lower end the scale K_3 carries a needle for taking the level of the mercury in the reservoir and on the upper end a vernier W_4 which takes the reading from the scale K_2. The distance between the point of the needle and the zero of the vernier W_4 is fixed and equal to 700 mm. This latter device is used for the calibration of the manometer.

Finally the whole apparatus is fixed on a wooden board and the board on a table.

3.2. Details of construction

The apparatus was designed in the University of Glasgow and the main parts constructed by an outside contractor. The main parts of the apparatus are of 'Pyrex' glass. All the cocks are high vacuum cocks.

The cylindrical parts of the volumetric tube have a capacity of 1/58.2 cm^3/mm of length.

Referring to equation (12)

$$\left.\begin{aligned} V_o &= 5.5 \text{ cm}^3 \\ x_o &= 482.5 \text{ mm} \\ u_o &= \frac{1}{35} \text{ cm}^3\text{/mm of length} \end{aligned}\right\} \quad \text{(30)}$$

Special care was taken during the blowing of the glass apparatus to give the parts an upward inclination so as to avoid trapping air or water in the different parts of the apparatus. The reservoir R was made from transparent perspex for reading the levels of the mercury. Stopper S_2 has a thick layer of rubber for cushioning the shock should the reservoir be lowered too quickly.

3.3. Operation

It is most important for the accuracy of the results to ensure that the apparatus is air-tight. This can be done by adequate lubrication of the cocks and good arrangement of the rubber-mercury sealings. If there is some leakage into the apparatus this can be checked by the following procedure:

The reservoir R is fixed in a certain position and the readings of the barometer H_1 and x_1, x_1^1 are taken. After some period of time (1 or 2 hours) the readings H_2, x_2 and x_2^1 are taken again. An estimate of the leakage in the manometer limb will be given by

$$(H_2 - x_2) - (H_1 - x_1)$$

and for the spraying chamber limb by:

$$(H_2 - x_2^1) - (H_1 - x_1^1)$$

To expel any air which may have leaked into the manometer the mercury reservoir is raised until the top of the mercury column is at the bulb Y. Cock D is then opened and by further raising the reservoir the mercury is forced slowly through the bore of the cock until it fills half of the vessel above. A similar procedure is followed for expelling the air from the volumetric tube through the tube II on the top of the cock A.

The method suggested for drawing in the sample of water is described in Section 2.3 (ii)a. After taking the 10 cm^3 sample of water, cock A is closed, C is turned to its large bore, cock B to position 1 (Fig. 3) and the reservoir is lowered to the lowest position. When the sample has dropped into the bulb X, stopper S_3 is put to the operation position, cock B is turned to position 2 and the reservoir is raised rapidly. After the whole sample of water has been sprayed and mercury has filled the funnel-shaped lowest part of the spraying chamber, cock B is turned to position 1 and the reservoir lowered. This procedure is repeated for the necessary number of sprays (12 sprays).

At the end of the last spray the stopper S_3 is turned off and with B in position 2 the reservoir is raised until the mercury reaches the level of the nozzles. Then C is turned to the small bore and B to position 1. The reservoir is raised as much as possible and then slowly lowered until the level of the water reaches the 1 cc mark. Cock C is now closed.

Using the verniers W_3 and W_2 respectively the readings x_1 and x_1^1 are found. After taking the readings x_1 and x_1^1, C is opened to the small bore and by raising the reservoir the released gases are compressed. Then A is turned to connect the volumetric tube with II and the released gases are expelled. Now by closing A and bringing the water level to the 1 cc mark the readings x_2 and x_2^1 can be taken.

3.4. Calibration of the manometer

Substitution of the values of V_0, x_0, u_0 from equation (30) in equation (12) leads to

$$\frac{675-x}{35} \; p_a = CT \qquad (31)$$

The actual variation of p_a with x can be found by calibation, which is carried out as follows:

Using cock C with its large bore, R is moved until the mercury in the manometer rises to a desired x and then R is fixed by tightening the string on T, Fig. 3. After waiting until the mercury settles down and with the needle on the lower end of the scale K_3 the level of the mercury in the reservoir can be read. Vernier W_3 is used to take the reading x and vernier W_4, the reading y, the distance between the zero of the vernier W_4 and the zero of the scale K_2.

If H is the atmospheric pressure in mm Hg during the experiment then the pressure above the mercury column in the manometer is:

$$p_a = H - (700+x-y) \qquad (32)$$

By changing x the curve $p_a = f(x)$ can be plotted from equation (32).

3.5. Lubrication of the cocks

The air-tightness of the apparatus depends on good greasing of the cocks. The following kinds of greases were found most satisfactory.

For the cocks *A* and *D* which are under vacuum all the time "Apiezon" gave good results. For the low temperature of the laboratory however especially early in the morning, "Apiezon" becomes very stiff and the cocks had to be warmed with a piece of cloth wetted in hot water.

For the cocks *B* and *C* which have to be turned many times during the experiments "silicone grease" was used which is soft even under relatively low temperature.

The following method of greasing was found to be best: with the cock slightly warm a small amount of grease was smeared evenly along two diametrically opposite lines. The cock was then placed in the socket and turned a few times, until the surface of the cock was clear of lines.

The amount of grease used must be the absolute minimum necessary because part of the grease may be trapped in the bores of the cocks and contaminate the apparatus.

3.6. Cleaning the apparatus

After operation for some time, due to the repeated greasing of the cocks and oxidation of mercury, the apparatus becomes contaminated and needs to be cleaned. One method is to dismantle it and soak the different parts for one day in carbon tetrachloride, later cleaning them in concentrated nitric acid and washing them thoroughly.

If the apparatus is only contaminated with grease, however, it is not necessary to dismantle it. Using the mercury reservoir carbon tetrachloride can be sucked into the apparatus and left for one day. After expelling the carbon tetrachloride the apparatus is washed with warm soap solution by moving the reservoir of mercury up and down. Finally it is washed with water. After cleaning, regreasing of the cocks is necessary.

4. EXPERIMENTS

4.1. Necessary number of sprays with the modified apparatus

The necessary number of sprays (n^*) is defined as the number of sprays after which more sprays show no distinct increase in the partial pressure of the released gases. Two methods were used for the determination of n^*.

(i) Using the *same sample of water* the readings x_1 and x_1^1 after each spray were taken for up to 25 sprays. Then the released gases were expelled and the readings x_2, x_2^1 were taken. The partial pressures of the released gases constrained in 1 cm^3 volume after each

spray were calculated from equation (10). The results are shown in Fig. 7. From this it is seen that $n^* = 8$.

(ii) In the second method the sample of the water was replaced after each series of sprays. Samples with the same air content were used. The first sample of water was thus sprayed once. After taking the readings x_1 and x_1^1 the released air was expelled and the readings x_2 and x_2^1 were taken. Then the water was replaced by a new sample which was sprayed twice, and so on. The partial pressures of the released gases constrained in 1 cm^3 volume after each series of sprays were calculated from equation (10) and the results are shown in Fig. 8. From this figure $n^* = 12$.

The difference in the results of the two methods is due to the greater time which is taken for the corresponding number of sprays in the first method. For example, the time which elapses in the first method for taking the readings x_1 and x_1^1 after the 6th spray is about 10 min., while the corresponding time in the second method is only 2.5 min. Evidently the correct method of determination of n^* is the second method because the procedure is similar to the actual experiments for the determination of the gas content.

4.2. Calibration of the manometer of the present apparatus

The variation of p_a with x can be found from equation (32). Because interest lies in the differences $(p_{a_1} - p_{a_2})$ it is more convenient to plot the curves $p_a = f(x)$ by putting $p_a = o$ for an arbitory minimum value of x. The calibration curves are shown in Fig. 9 and they have been plotted with $p_a = o$ for x=250 mm. The curve (a) represents the variation of p_a with x immediately after expulsion of the air which has leaked into the manometer. From this curve it can be seen that the difference $p_{a_1} - p_{a_2}$ for x_1=475 mm and x_2=250 mm is only 0.6 mm Hg. Curve (b) refers to the conditions after the first test for the determination of the gas content of a sample of the water. Curve (c) represents the variation of p with x after the second test for the determination of the gas content while the curve (d) shows the conditions in the manometer after the fifth and twentieth test.

Thus it is suggested that after regreasing the cock D and expelling the air from the manometer some preliminary tests should be made before determining the calibration curve (d) which will be correct for a large number of experiments, that is until the next regreasing of the cock D. From the curve (d) it can be seen that the difference $(p_{a_1} - p_{a_2})$ for x_1=475 mm and x_2=250 mm is 3.5 mm Hg.

For a high air content with $x_1 - x_2$=160 mm (x_1=445 x_2=285) $p_{a_1} - p_{a_2}$=2.8-0.2=2.6 mm Hg, e.g. by neglecting the term $(p_{a_1} - p_{a_2})$ the error is 1.6%.

4.3. Determination of the gas content which remains in solution after the first set of sprays $(\Delta p_2 + \Delta p_3)$

From equations (26) and (27) the pressure (Δp_2) of the gases released from the second set of sprays and constrained in 1 cm^3 volume may be calculated. In the present apparatus the section of the

volumetric tube between the 10 and 11 cm^3 marks is cylindrical with a capacity of 1/58.2 cm^3/mm. Thus equation (27) can be written:

$$\Delta p_2 = \Delta p_2^1 \frac{1}{1.465 - \frac{x_3^1}{582}} \qquad (33)$$

The factor

$$\frac{1}{1.465 - \frac{x_3^1}{582}} = 1 \text{ for } x_3^1 = 271 \text{ mm}$$

which corresponds to the 11 cm^3 mark, that is when no loss of water takes place. Similarly for the conditions after the third set of sprays equation (27a) is transformed into:

$$\Delta p_3 = \Delta p_3^1 \frac{1}{1.465 - \frac{x_5^1}{582}} \qquad (34)$$

Results of a number of experiments are tabulated in Table 1. The second column of this table contains the values of p^1 calculated from the experiments using

$$p^1 = (x_1 - x_2) + (p_{a_1} - p_{a_2}) + 0.927\ (x_2^1 - x_1^1) \qquad (35)$$

The third column contains the values of Δp_2 as calculated from equation (26) and (33). The fourth column contains Δp_3 calculated from equation (26a) and (34). The sixth and seventh columns contain e_2 and e_3 which are the corresponding Δp_2 and Δp_3 expressed as percentages of p^1. Finally, the eighth column contains e which is the sum $e_2 + e_3$.

From Table 1 the mean value of e is 4%, i.e. by neglecting the terms $(\Delta p_2 + \Delta p_3)$ the error introduced is 4%. This conclusion results from experiments with samples of about the same air content. According to Henry's law, however, this conclusion can be extended over the complete range of air content.

The great difference between the actual (4%) and theoretical value (1.09%) (found in Section 2.2 (ii)) for the amount of gases which remain in solution after the first set of sprays means that the assumption on which the theoretical calculations were based was not correct. This assumption was that the sample of water was saturated under conditions which existed immediately after the end of the last spray. From the calibration curves for the necessary number of sprays (Figs. 7 & 8) it is seen that there is no distinct increase in the pressure of the released gases after the 12th spray. All the absorption or extraction curves, however, show a very rapid increase or decrease of the dissolved gas at the beginning of the process, but the rate decreases soon and asymptotically tends to zero. Consequently there is no distinct difference in the pressure of the released gases from the 12th to 20th spray but there will be some distinct difference between the 12th and say 300th spray. Unfortunately due to possible leakages it was not possible to reach such a high number of sprays.

It is found that after the first set of sprays the sample still contains 4% of the initial gas. After the second set of sprays the

sample contains 4% of 4% = 0.16% of the initial gas, and after the third set of sprays the remaining gas in the water will be 0.16% of 4% = 0.0064% which is beyond the accuracy of the apparatus.

Tests were made using fourth and fifth sets of sprays, the results of which justify the assumption that there is no reason to continue spraying the sample after the third set of sprays.

4.4. Determination of the air content in a number of samples of water with the same air content

Different samples of water were taken from a relatively large reservoir which contained tapwater exposed for several days to the atmosphere. The water was thus saturated with air. Care was taken to draw all the samples into the apparatus under the same conditions. The temperature of the experiments was 20°C and the atmospheric pressure 763 mm Hg. Results are shown in Table 2. The second column of this table contains the different values of p'' where

$$p'' = (x_1 - x_2) + 0.927\ (x_2^1 - x_1^1) \qquad (36)$$

The third column contains the values of p' which are given by equation (35) or by

$$p' = p'' + (p_{a_1} - p_{a_2}) \qquad (37)$$

The fourth and fifth columns give Δp_2 and Δp_3 and the sixth column shows the sum $\Delta p_2 + \Delta p_3$. The seventh column gives p^* e.g. the pressure in mm Hg of the total air content in the sample reduced to 1 cm^3 volume under 20°C temperature given by equation (28) or by

$$p^* = p' + (\Delta p_2 + \Delta p_3) \qquad (38)$$

Finally the last column gives the volume of the total air content (V^*) referred to N.T.P. which is calculated from equation (29). From this table the mean value of p^* is 176.85 mm Hg and the scattering of the results is within the limits 176.85 ±1%.

4.5. Comparison of the M.E.R.L. apparatus with the modified apparatus

All the errors included in Section 2.3 and referring to the present apparatus appear also when using the M.E.R.L. apparatus. Some of the errors in the latter are greater than in the present apparatus. Some additional errors are introduced by using the formula (8) and thus neglecting the terms $(p_{a_1} - p_{a_2})$, $0.927(x_2^1 - x_1^1)$ and $\Delta p_2 + \Delta p_3$ which appear in the complete formula (28).

(i) **Error introduced by neglecting the term $(p_{a_1} - p_{a_2})$**

In the M.E.R.L. apparatus

$$\left.\begin{aligned} V_o &= 0.515\ cm^3 \\ x_o &= 300\ mm \\ \text{and}\quad u_o &= \frac{1}{48.5}\ cm^3/mm \end{aligned}\right| \qquad (39)$$

Then equation (12) for the M.E.R.L. apparatus becomes

$$\frac{325-x}{48.5}\ p_a = C'T \qquad (40)$$

For the present apparatus equation (31) gives

$$\frac{675-x}{35}\ p_a = CT \qquad (40a)$$

Suppose now that in both units $x_1 - x_2 = 100$ mm. What will be the difference $(p_{a_1} - p_{a_2})$ in the M.E.R.L. apparatus if it is assumed that in both units the amount of leakage is the same (i.e. $c = c'$) and if in the present apparatus $p_{a_1} - p_{a_2}$ is found to be 0.5 mm Hg. The value of x_2 is about 285 mm in the present apparatus and 166 mm in the M.E.R.L. apparatus. From equations (39) and (40) it is found that the difference $(p_{a_1} - p_{a_2})$ in the M.E.R.L. apparatus is 8.3 mm. Therefore by neglecting the term $(p_{a_1} - p_{a_2})$ in the modified apparatus the error is +0.5% while in the M.E.R.L. method it is +8.3%. This error increases as the difference $x_1 - x_2$ increases (equation (14)). In fact, if instead of constraining the released gases into 1 c.c. volume we constrain them into 2 cm^3 volume the difference $x_1 - x_2$ will be about 50 mm. $(p_{a_1} - p_{a_2}) = 2.3$ mm for the M.E.R.L. apparatus and the error introduced by neglecting $(p_{a_1} - p_{a_2})$ will be +4.6% instead of +8.3%.

In order to find the actual variation of p_a with x in the manometer of the M.E.R.L. apparatus the system shown in Fig. 10 was used. The stand S carries the ring clamp Q by which the position of the mercury reservoir R can be adjusted. With the needle N the height (y) of the horizontal plate P above the mercury level in R can be measured. The height of the zero of the manometer scale above the surface of the plate P is 260 mm. The pressure above the mercury column in the manometer will be given by

$$p_a = H - 260 - (x + y) \qquad (41)$$

In Fig. 11 the variation of p_a with x is plotted for different conditions. The curves a, b, c and d have the same meaning as explained in Section 4.2.

(ii) **Error introduced by neglecting the term** $0.927\ (x_2' - x_1')$

In the present apparatus by making the section of the volumetric tube cylindrical between the 10 and 11 cm^3 marks and by providing the vernier W_2, x_1' and x_2' can be exactly measured. In the M.E.R.L. method the above term is neglected. The difference $x_2' - x_1'$ varies from 1 to 3 mm if the released gases were constrained in 1 cm^3 volume and from 0.5 to 1.5 mm if the gases were constrained in 2 cm^3 volume.

Thus in the previous example with $x_1 - x_2 = 100$ mm the error introduced by neglecting term (ii) is from 0.93 to 2.78%. For low values of air content with $x_1 - x_2$ say 10 mm the error introduced by neglecting term (ii) varies from 9.3 to 27.8%.

(iii) **Error introduced by neglecting the term $\Delta p_2 + \Delta p_3$**

From a number of experiments it is found that the amount of gases which remains in solution after the first set of sprays is about 4% expressed as percentage of $x_1 - x_2$.

Consequently from (i), (ii) and (iii) above it is concluded that the accuracy of the M.E.R.L. apparatus depends greatly on $x_1 - x_2$ i.e. upon the magnitude of the air content. The variation of the accuracy with $x_1 - x_2$ when the released gases are constrained in 1 cm^3 volume is shown in Fig. 12 and when the released gases are constrained in 2 cm^3 volume in Fig. 13. In these figures x_2 is taken to be 166 mm.

4.6. Period of time necessary for determination of the air content of a sample of water

The necessary periods of time for each phase of the experiments were measured in both the modified and the M.E.R.L. apparatus and the results are shown in Table 3. The total time for one experiment - from the instant of being ready to draw in the sample of the water until the sample is expelled i.e. after taking the readings x_1 and x_2 - with the modified apparatus was 4 min 10 sec, while the corresponding time for the M.E.R.L. apparatus was found to be 6 minutes.

5. SIMPLIFICATION OF THE METHOD OF CALCULATING THE PARTIAL PRESSURE OF THE TOTAL GAS CONTENT OF A SAMPLE

The pressure of the total gas content of a sample of water if the gases are released and constrained in 1 cm^3 volume is given by equation (28)

$$p^* = p_o + (p_{a_1} - p_{a_2}) + 0.927\ (x_2^1 - x_1^1) + \Delta p_2 + \Delta p_3$$

from which

$$\frac{p^*}{p_o} = 1 + \frac{p_{a_1} - p_{a_2}}{p_o} + 0.927\ \frac{x_2^1 - x_1^1}{p_o} + \frac{\Delta p_2 + \Delta p_3}{p_o} \qquad (42)$$

where, by equation (8),

$$p_o = x_1 - x_2$$

For each re-greasing of cock D and expelling of the leaked air from the manometer, after the 5th test, curve (d) (Fig. 9) was found to be the same. The value of x_2 is about 285 mm for the modified apparatus.

From curve (d) (Fig. 9) the curve

$$\frac{p_{a_1} - p_{a_2}}{p_o} = \varphi(p_o) \qquad (43)$$

can be plotted, where

$$p_o = x_1 - 285 \qquad (44)$$

This curve is shown in Fig. 14. Because $\frac{\Delta p_2 + \Delta p_3}{p_o} \simeq 4\%$ for all the values of p_o the same curve in Fig. 14 may represent the variation of where

$$\lambda = \frac{p_{a_1} - p_{a_2}}{p_o} + \frac{\Delta p_2 + \Delta p_3}{p_o} \qquad (45)$$

Thus if x_1, x_1^1 and x_2, x_2^1 are determined for a given sample of water the pressure of the total gas content of the sample constrained in 1 cm^3 volume will be given by

$$p^* = (x_1 - x_2)(1 + \lambda) + 0.927 (x_2^1 - x_1^1) \qquad (46)$$

6. CONCLUSIONS

The assumptions made for the derivation of formula (8) have been proved incorrect. The error introduced by neglecting the variation of pressure above the manometric column increases as the air content of the sample increases. By neglecting the loss of water during the expulsion of the released gases the introduced error becomes large for low air content. This error varies between wide limits for samples with the same air content because it is not possible to control the amount of water which is lost every time. Finally it has been found that the sample of water after the first set of sprays still contains some amount of gases in solution and by neglecting that the introduced error is about 4% for the complete range of air content.

The present modified apparatus is accurate within the limits ±1% for water saturated with air under atmospheric conditions, i.e. for water with high air content. As follows from the theoretical analysis, however, the accuracy of this apparatus is expected to be about the same over the whole range of air contents with a slight deterioration for very low air contents due to the effect of the systematic errors.

Finally formula (46) greatly simplifies formula (28) and thus facilitates the calculation of the total gas content of a sample of water.

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LIST OF TABLES AND FIGURES

TABLES

FIGURES

Distribution - Group No. 8.

TABLE I. Determination of the gas content which remains in solution after the first set of sprays

No.	m.m. Hg.				$e_2 = 100\ \frac{\Delta p_2}{p^1}$	$e_3 = 100\ \frac{\Delta p_3}{p^1}$	$e = e_2 + e_3$
	p^1	Δp_2	Δp_3	$\Delta p = \Delta p_2 + \Delta p_3$			
1	165.9	5.50	1.50	7.00	3.32	0.93	4.25
2	167.1	5.25	1.65	6.90	3.14	0.99	4.13
3	168.5	5.70	1.50	7.20	3.38	0.89	4.27
4	168.8	5.55	1.10	6.65	3.29	0.65	3.94
5	170.3	6.25	1.75	8.00	3.66	1.03	4.69
6	170.7	4.35	1.80	6.15	2.55	1.05	3.60
7	170.8	5.05	1.10	6.15	2.96	0.64	3.60
8	170.9	4.70	1.55	6.25	2.75	0.91	3.66
9	171.4	5.00	2.00	7.00	2.92	1.17	4.09
10	173.2	6.25	0.75	7.00	3.60	0.40	4.00
11	174.8	4.70	1.35	6.05	2.69	0.77	3.46
12	177	6.45	1.50	7.95	3.64	0.85	4.49
13	177.2	6.40	1.70	8.10	3.61	0.96	4.57
14	177.4	4.70	2.00	6.70	2.65	1.13	3.78
15	178	4.65	1.65	6.30	2.62	0.93	3.55
16	178	5.65	2.00	7.65	3.18	1.12	4.30
17	178	4.70	2.00	6.70	2.64	1.12	3.76
18	178.1	5.80	1.55	7.35	3.26	0.87	4.13
19	178.2	6.25	1.80	8.05	3.50	1.01	4.51
20	180.7	5.25	1.55	6.80	2.90	0.86	3.76
			Mean Value		3.10	0.90	4.00

TABLE 2. Determination of the air content in a number of samples of water with the same air content

No.	m.m. Hg.						V^* cm^3 gas / litre H_2O
	p''	p'	Δp_2	Δp_3	$\Delta p_2 + \Delta p_3$	p^*	
1	167.70	169.00	6.40	1.35	7.75	176.75	21.65
2	167.00	168.45	5.70	1.50	7.20	175.65	21.50
3	165.85	167.35	5.85	2.00	7.85	175.20	21.48
4	169.45	170.90	4.70	1.55	6.25	177.15	21.73
5	169.75	171.25	5.40	0.80	6.20	177.45	21.76
6	170.05	171.95	4.60	1.90	6.50	178.45	21.85
7	168.05	170.25	6.25	1.75	8.00	178.25	21.82
8	168.50	170.70	4.35	1.80	6.15	176.85	21.65
Mean	168.30	170.00	5.40	1.57	6.97	176.97	21.70

TABLE 3. Period of time necessary for determination of the air content of a sample of water

Time in sec.

		M.E.R.L. Apparatus	Modified Apparatus
1.	Time necessary for introduction of the water sample into the apparatus	30	30
2.	Time required to drop the sample into the bulb below spraying chamber	46	18
3.	Spraying of water sample	180	90
4.	First reading	47	50
5.	Second reading	42	45
6.	Expulsion of water sample	15	17
	Total:	360	250

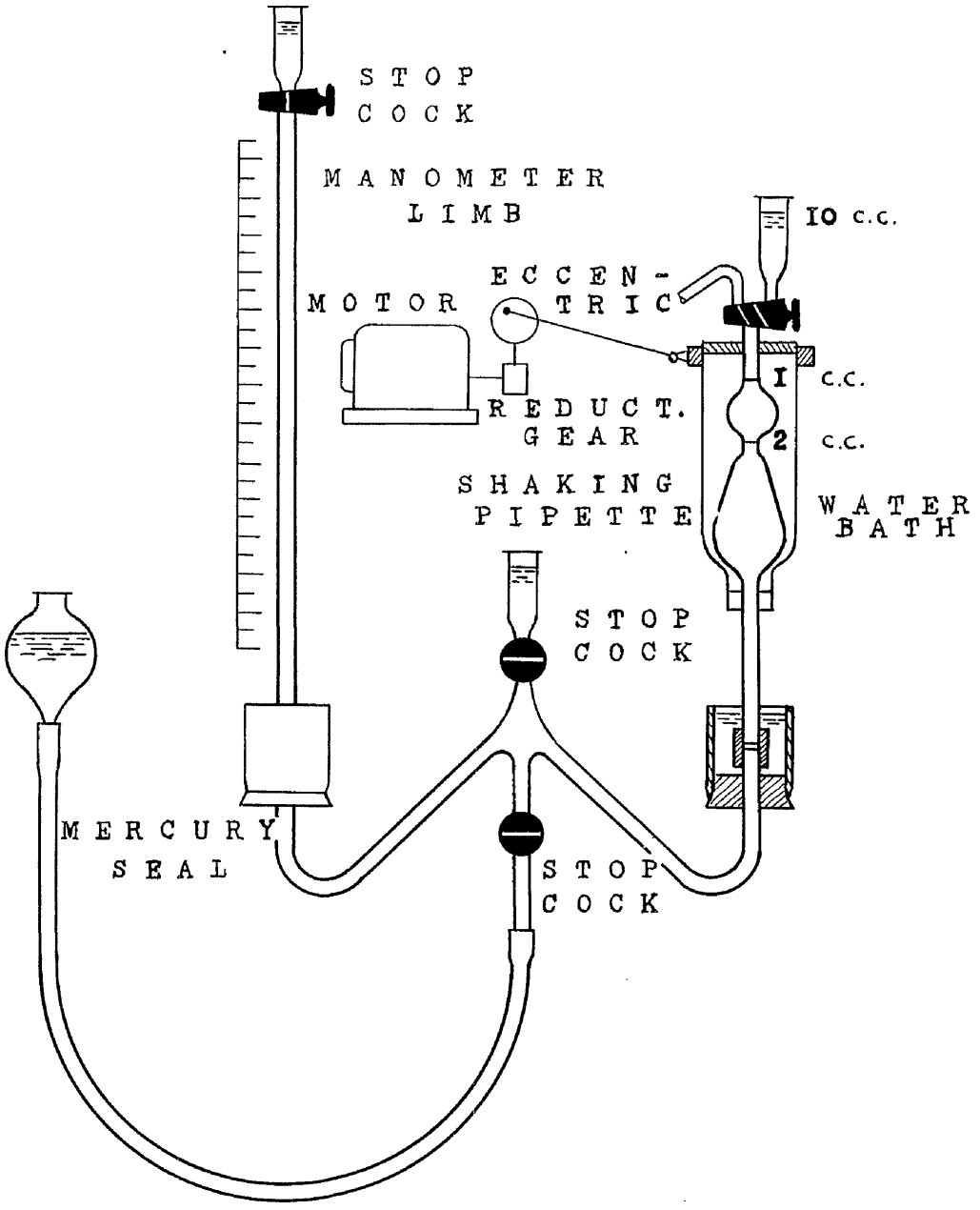


FIG. I. VAN SLYKE APPARATUS

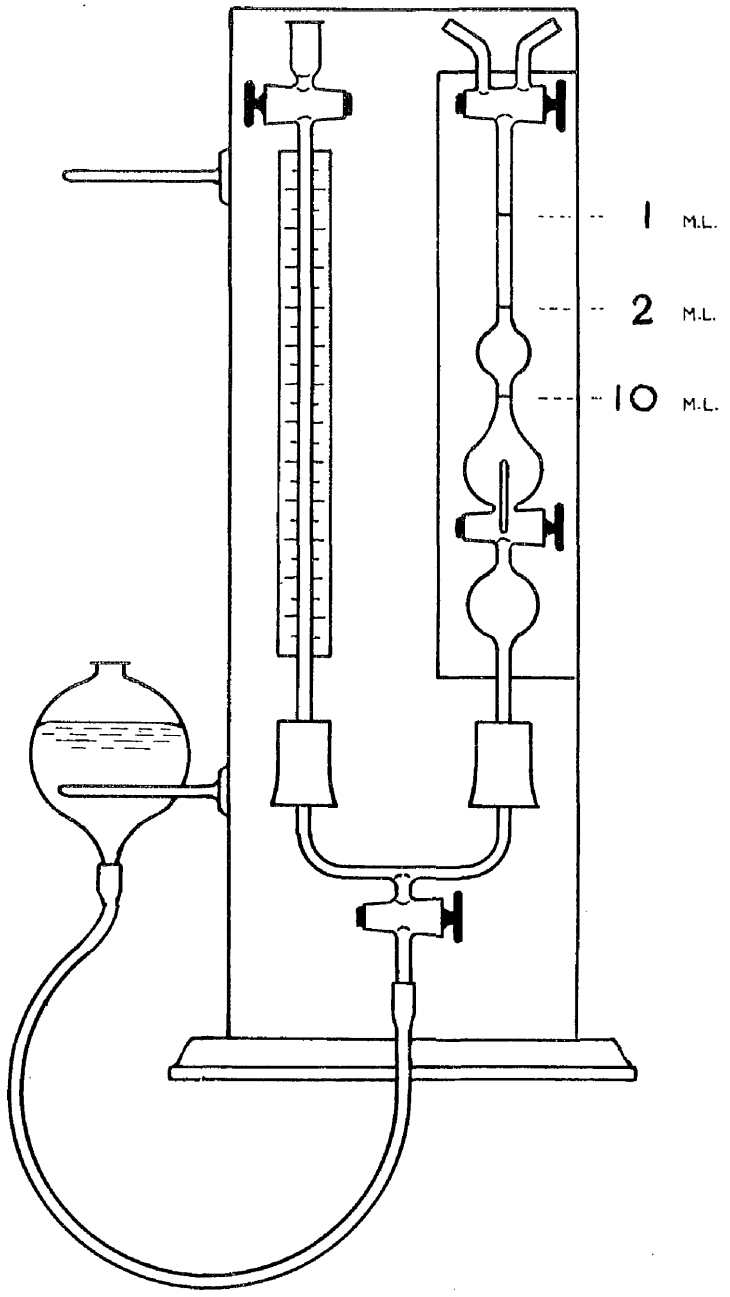
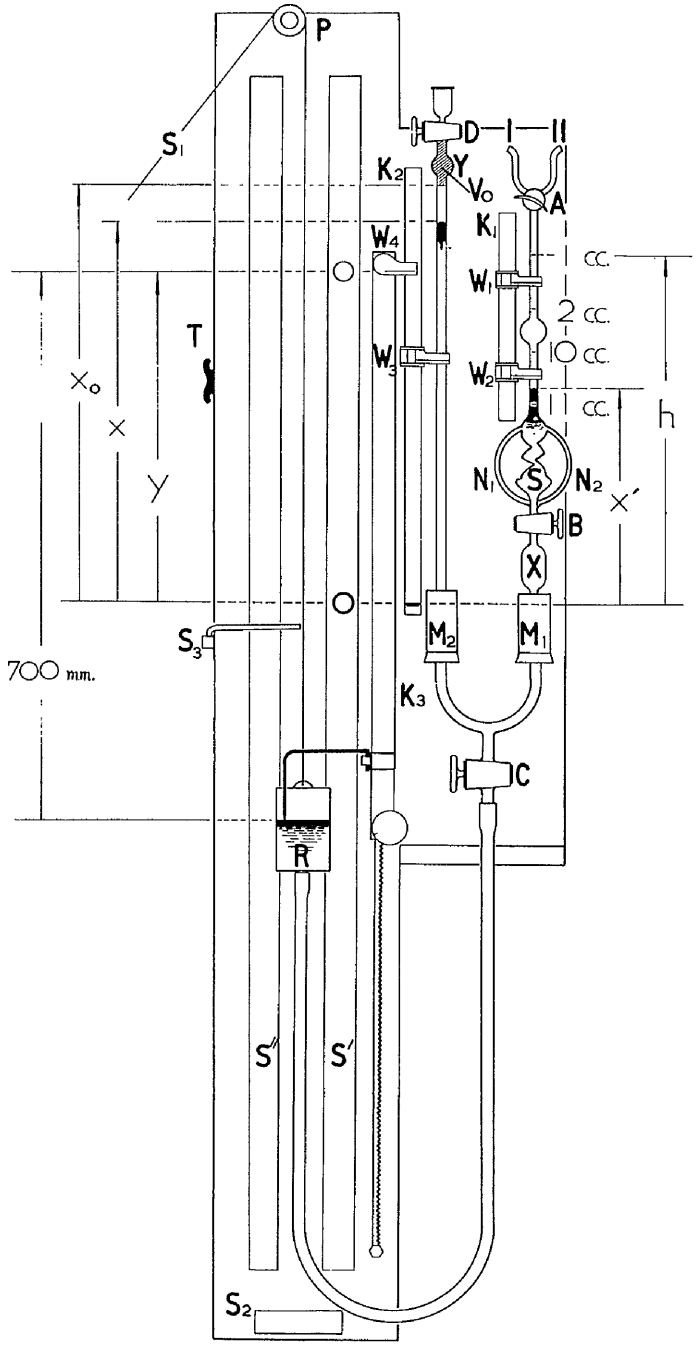
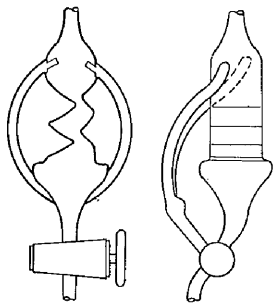
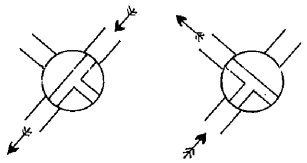


FIG. 2. M.E.R.L. APPARATUS



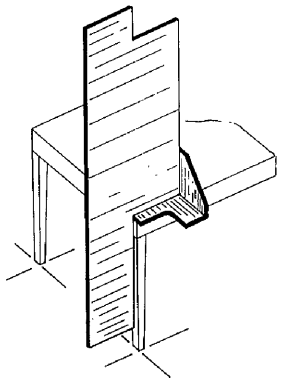


SPRAYING CHAMBER



POSITION I POSITION II

COCK B



DETAILS OF FIXING BOARD

FIG. 3. MODIFIED APPARATUS

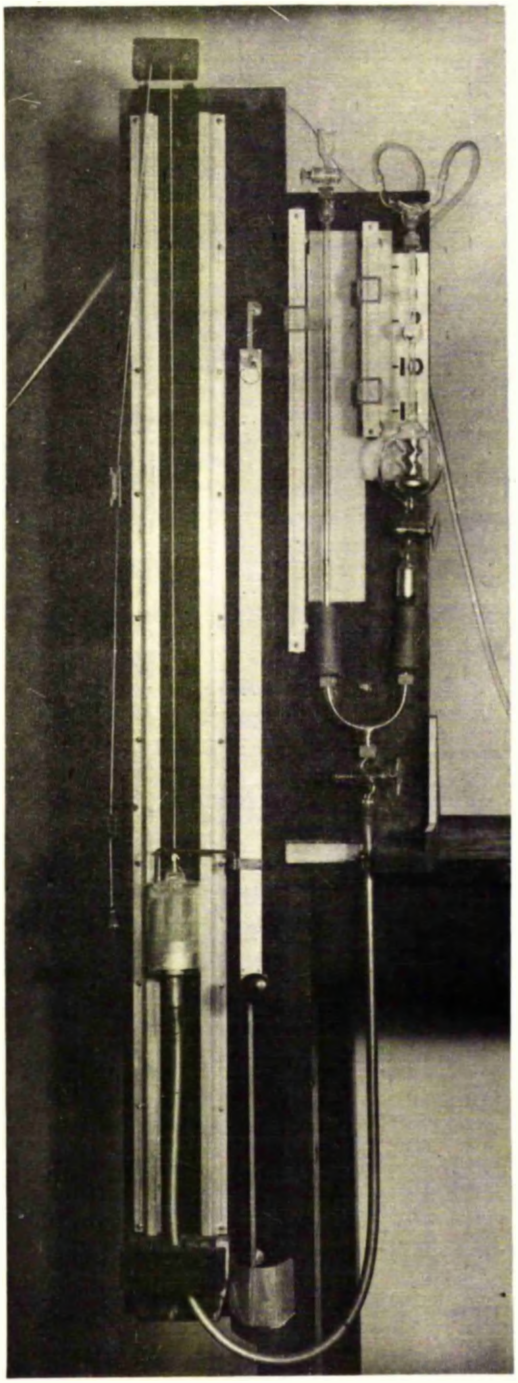


FIG. 4. VIEW OF MODIFIED APPARATUS

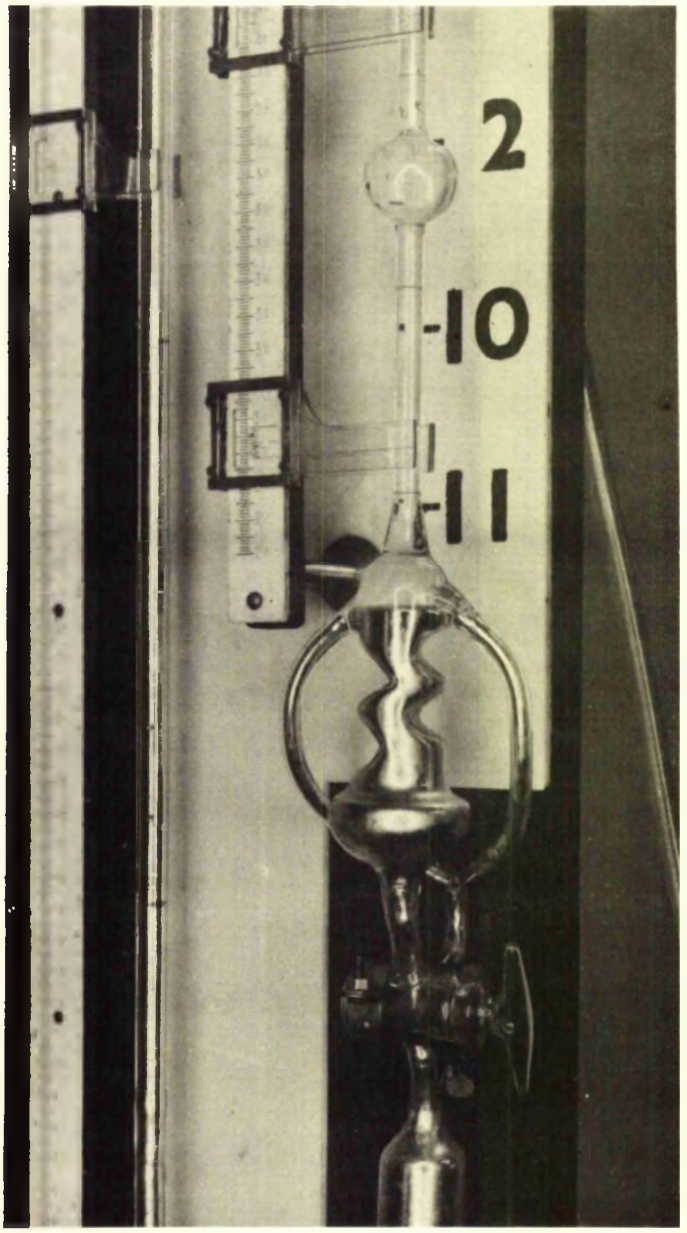


FIG. 5. VIEW OF SPRAYING CHAMBER

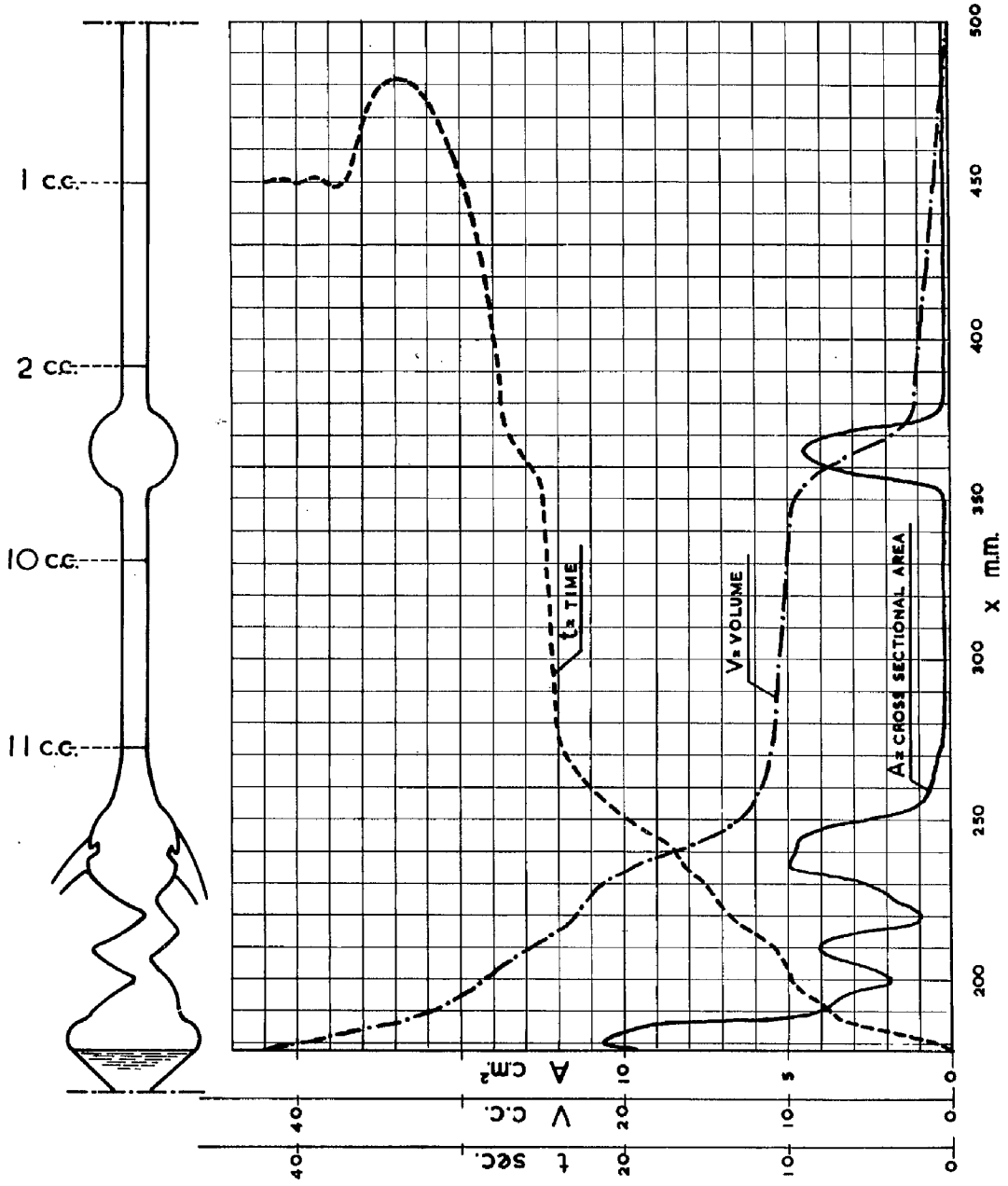


FIG. 6. CALIBRATION OF SPRAYING CHAMBER LIMB

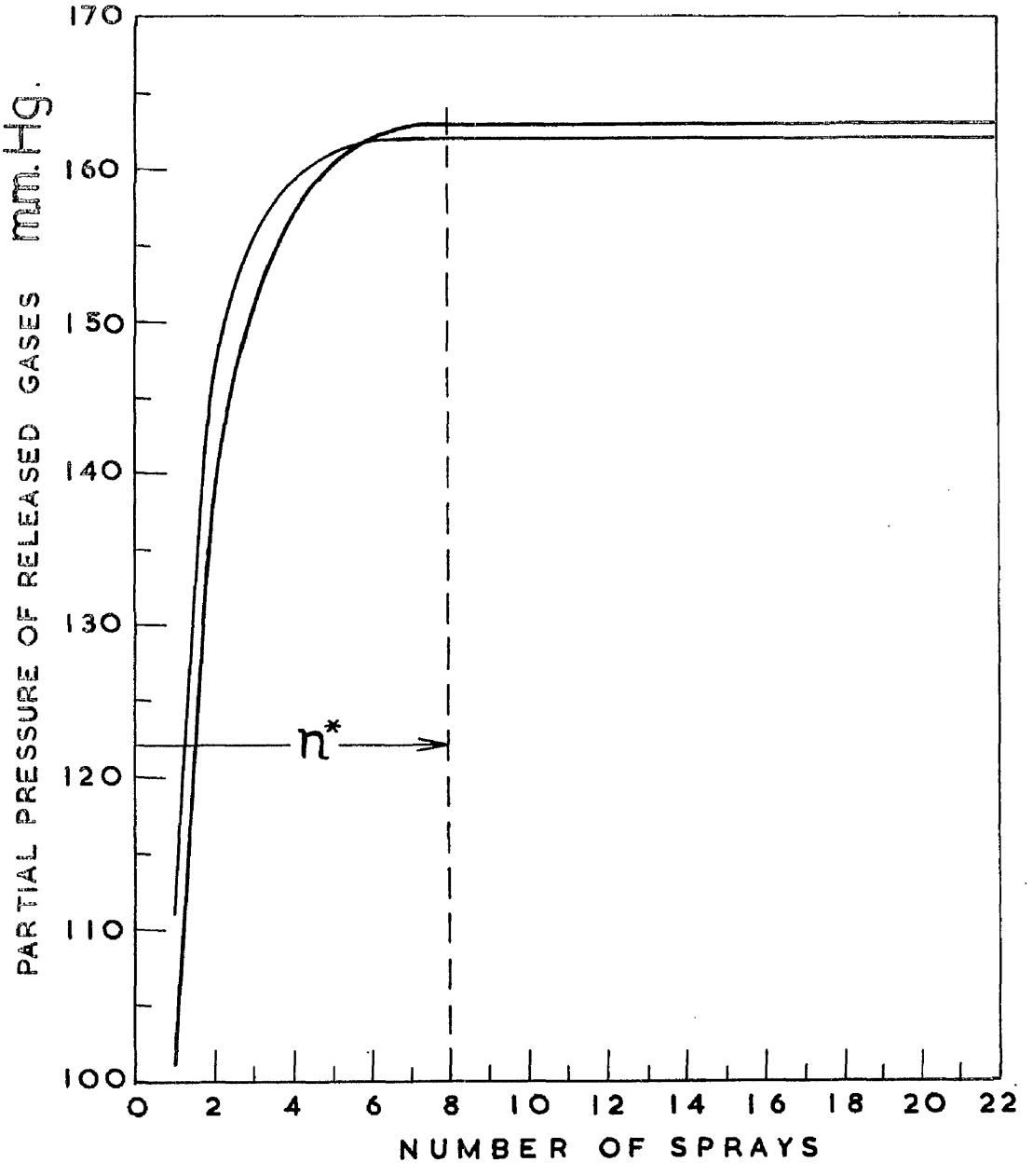


FIG. 7. CHOICE OF SUITABLE NUMBER OF SPRAYS. SAME SAMPLE

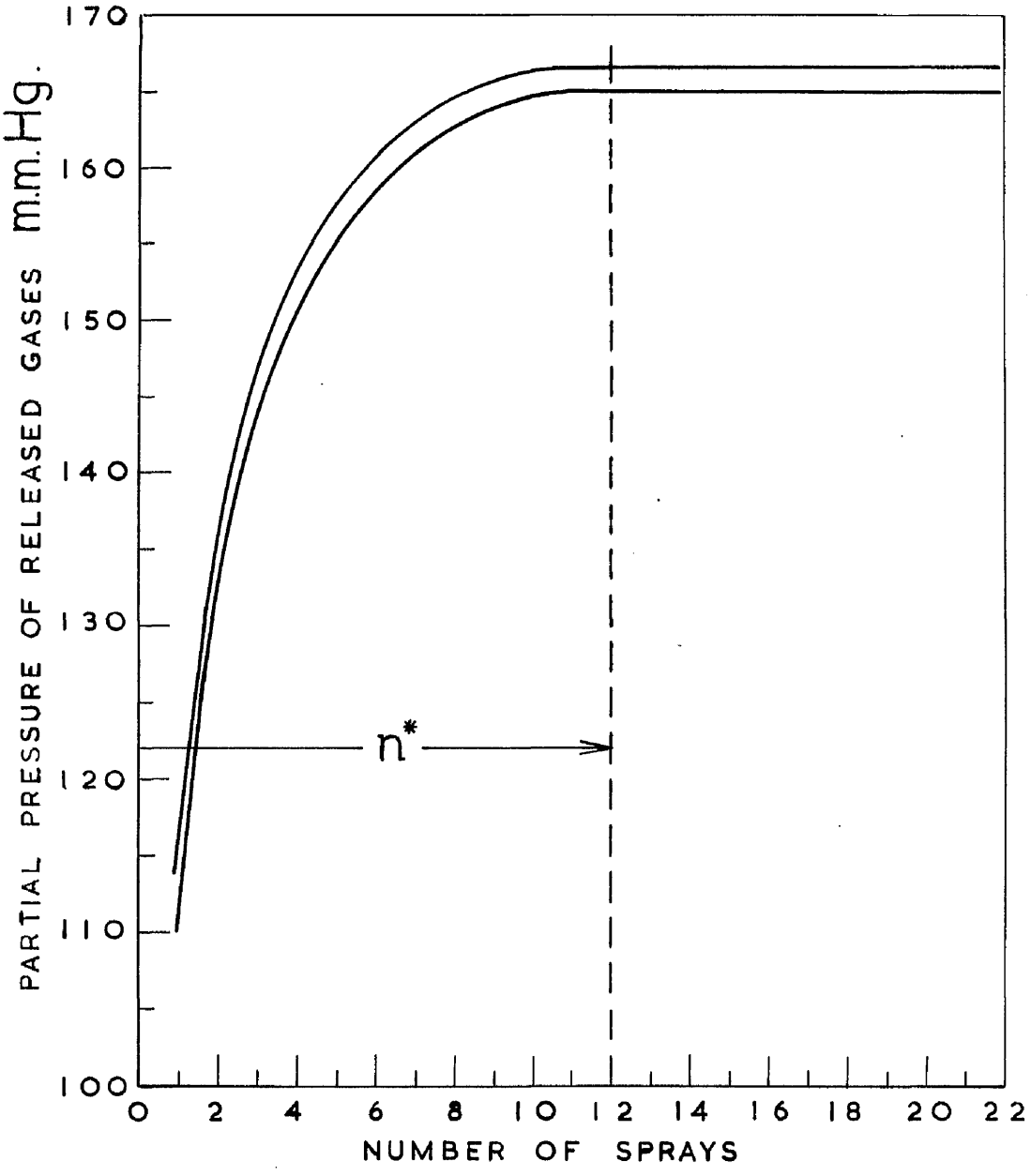


FIG. 8. CHOICE OF SUITABLE NUMBER OF SPRAYS. CHANGE OF SAMPLE

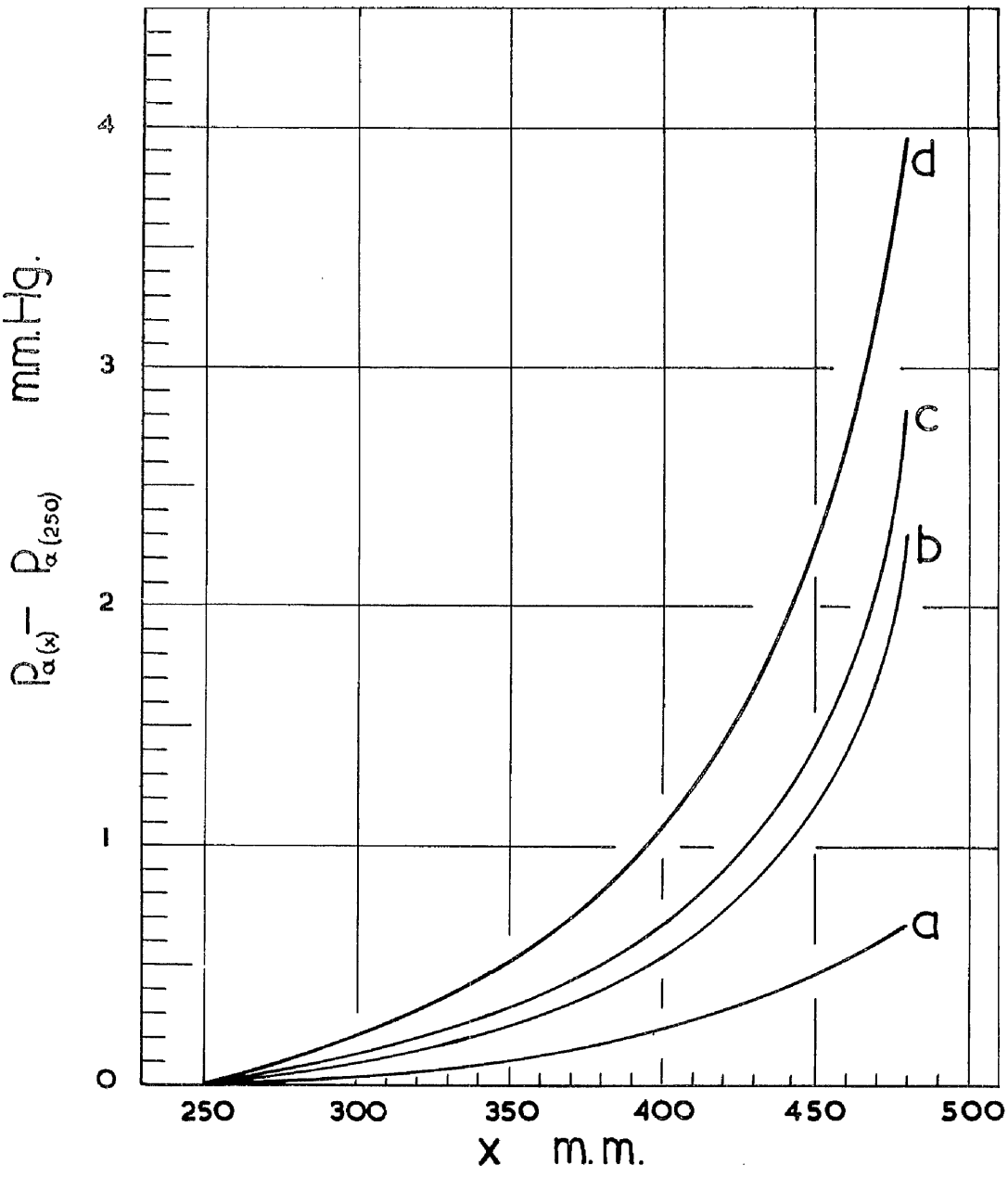


FIG. 9. MODIFIED APPARATUS: CALIBRATION OF MANOMETER

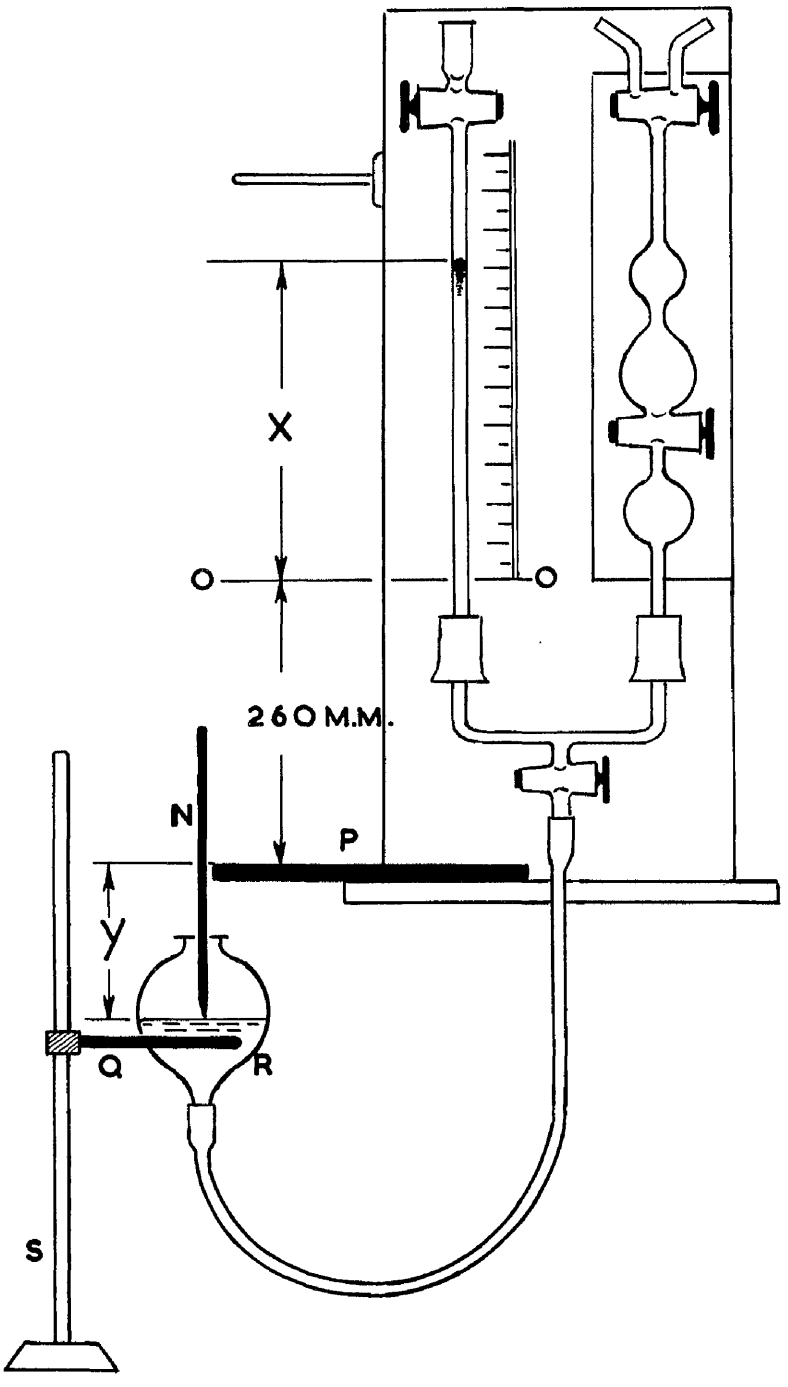


FIG. 10. METHOD OF CALIBRATING M.E.R.L. APPARATUS

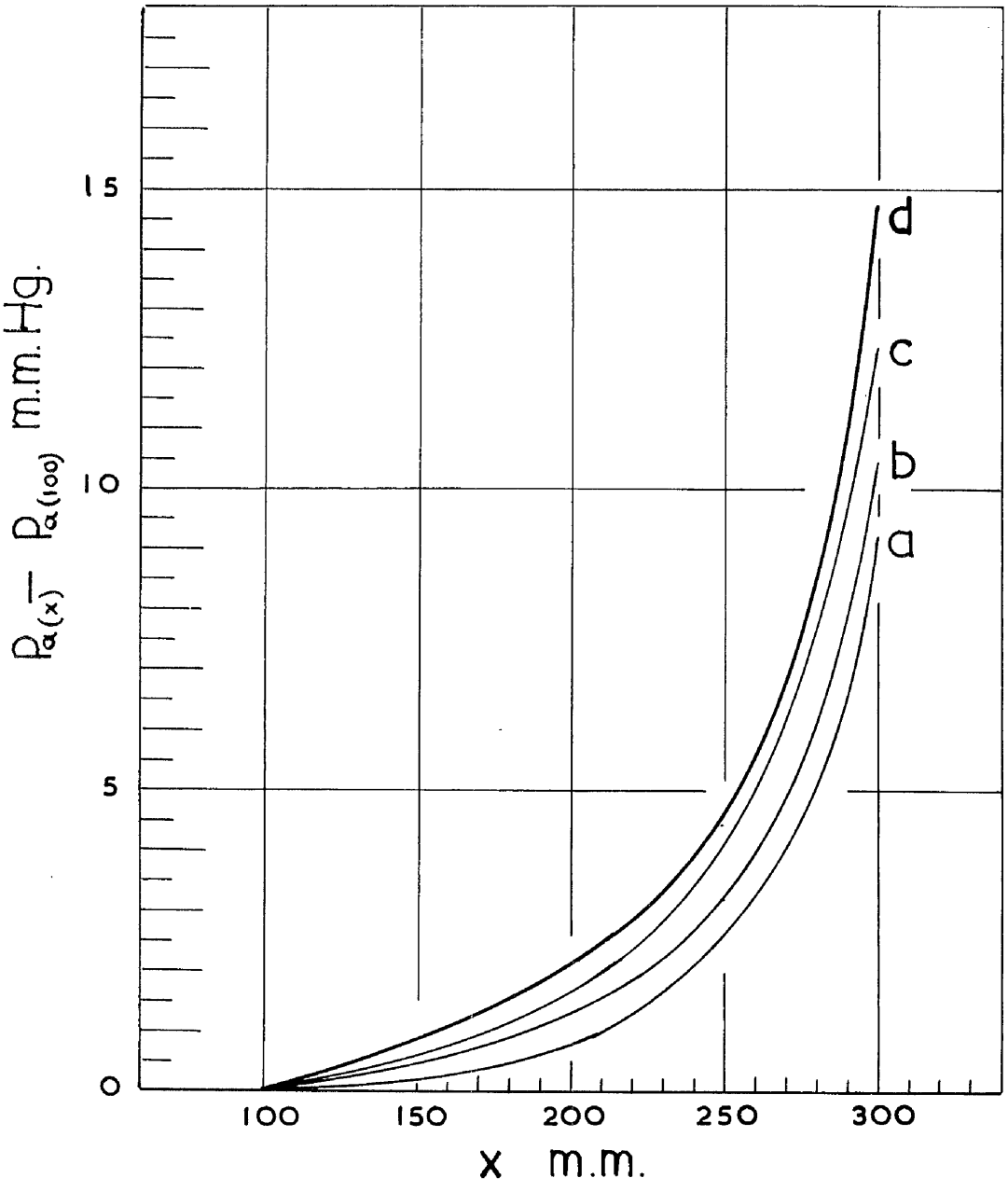


FIG. 11. M.E.R.L. APPARATUS: CALIBRATION OF MANOMETER

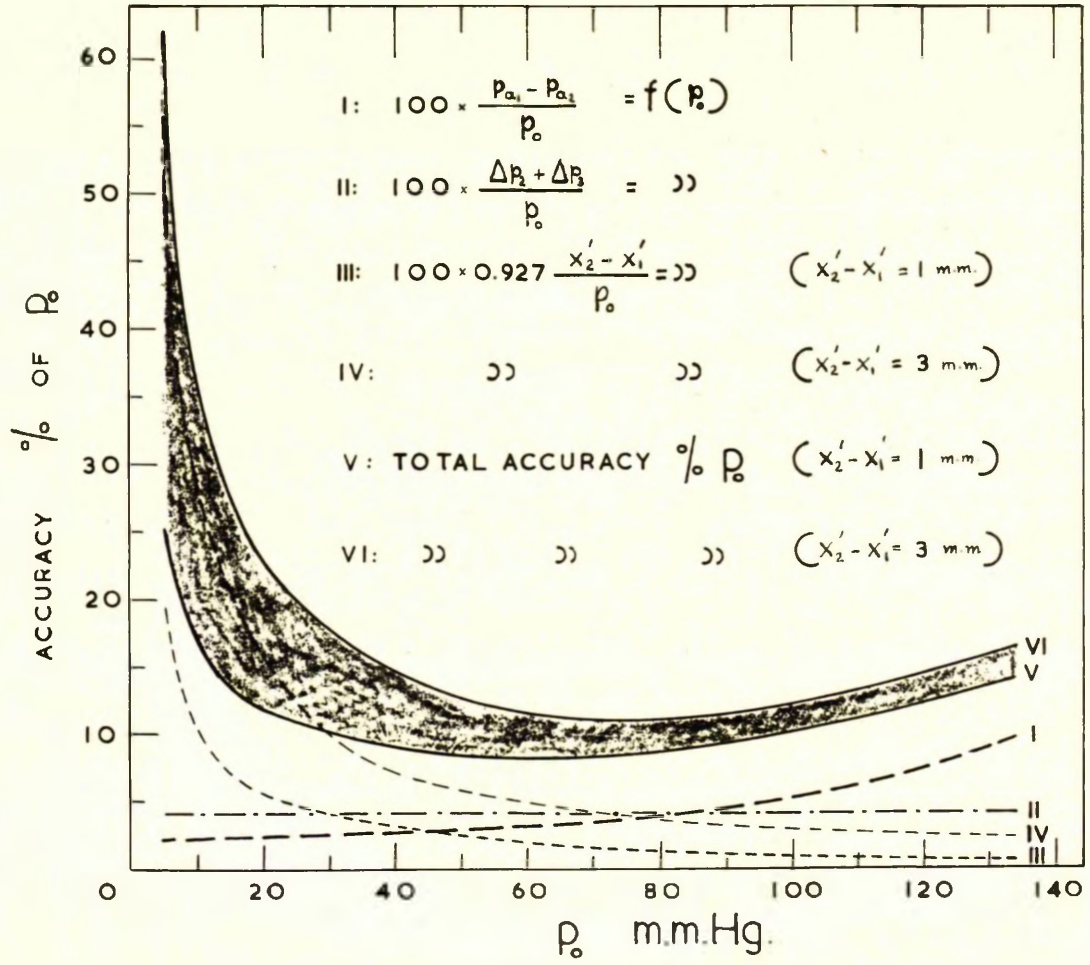


FIG. 12. ACCURACY OF M.E.R.L. APPARATUS PLOTTED ON AIR CONTENT. (GASES CONSTRAINED TO 1 c.c.)

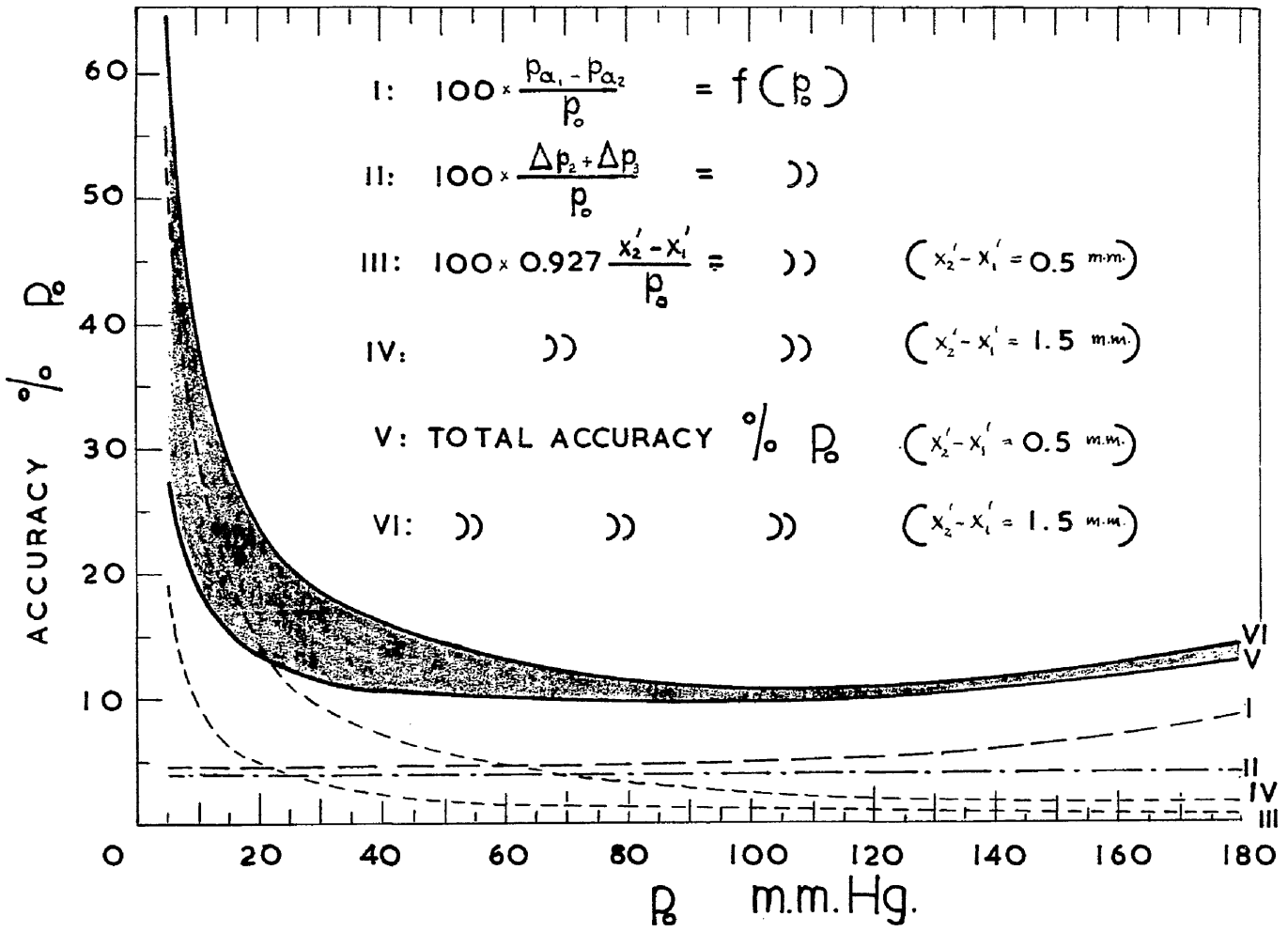


FIG. 13. ACCURACY OF M.E.R.L. APPARATUS PLOTTED ON AIR CONTENT. (GASES CONSTRAINED TO 2 c.c.)

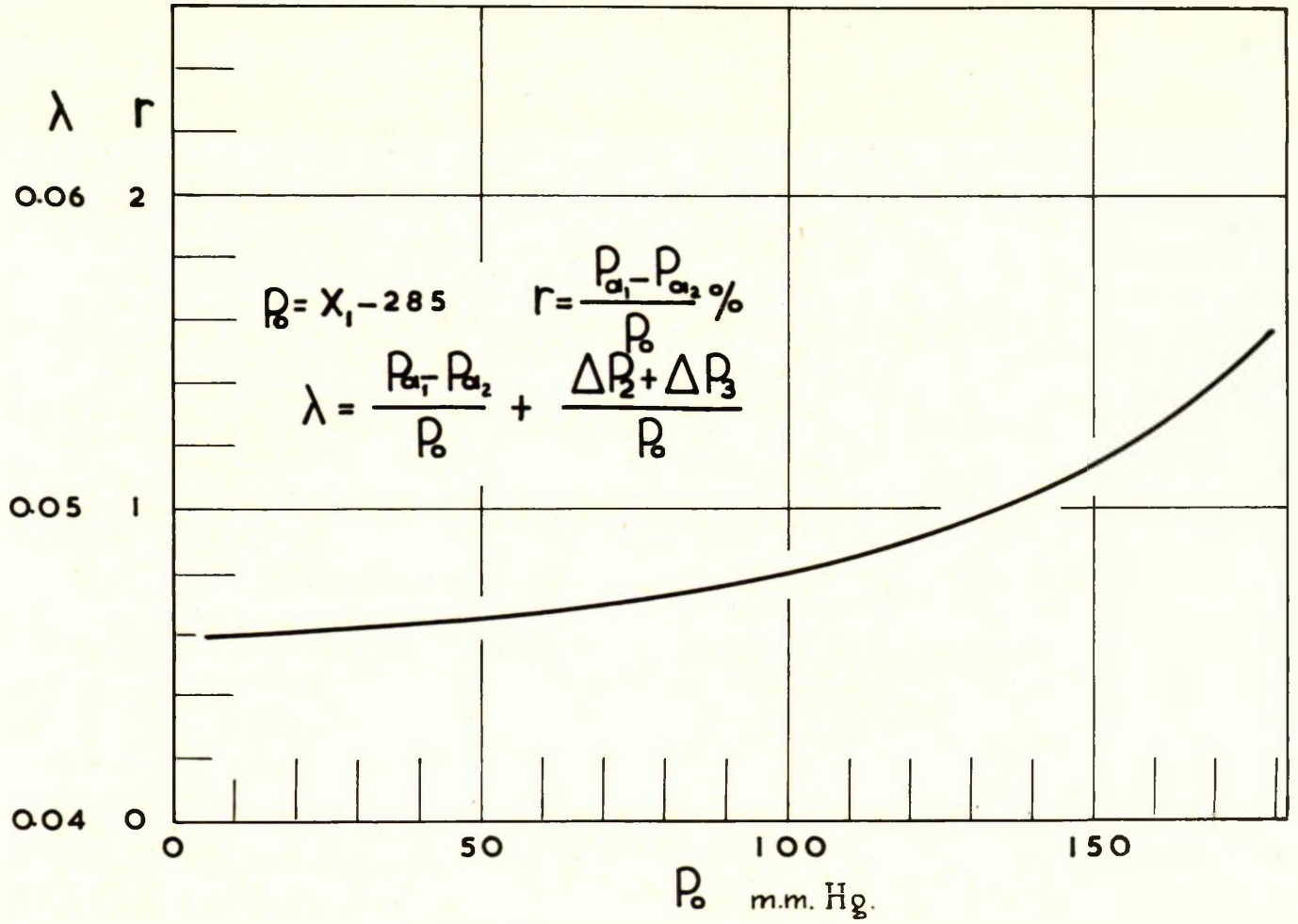


FIG. 14. VARIATION OF λ WITH P_o

MERL FLUIDS REPORT No 73

MECHANICAL ENGINEERING RESEARCH LABORATORY
FLUID MECHANICS DIVISION

Errors in Measuring the Gas Content of Water

E. V. KANELLOPOULOS

APPENDIX III

December 1958

Communications about this document should be sent to the
DIRECTOR, M.E.R.L., EAST KILBRIDE, GLASGOW

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

MECHANICAL ENGINEERING RESEARCH LABORATORY

ERRORS IN MEASURING THE GAS CONTENT OF WATER

by

E.V. KANELLOPOULOS, Dipl.Ing., M.I.M. and E.E.(Greece)

SUMMARY

New apparatus for measuring the gas content of liquids was described in MERL Fluids Report No. 69. The present paper is a continuation of that work, and involves the assessment of errors in the original MERL apparatus and methods of calculation. The gas-content apparatus depends on a spraying process for extracting the gas. When the spraying is finished, some gas remains in solution in the liquid, due to the presence of the released gas above the water. This proportion is assessed and it is shown how it varies according to the original gas content, giving a larger error in certain cases than in others.

CONTENTS

1. INTRODUCTION

In an earlier report[1], a new apparatus for measuring the total gas content of water by extraction was described. In principle it was similar to the MERL apparatus[2] but modifications, including changes to the spraying chamber, resulted in greater speed of operation and ease of handling. The present report is an extension to MERL Fluids Report No 69 and the numbering of the equations and figures follows in sequence so that the two reports may be read together. The notation is the same for both reports.

The purpose of this report is to show how the amount of gases which remains in solution in the water sample after the spraying process can be determined.

2. DEVELOPMENT OF EQUATIONS

Equation (17) of the previous report[1] was given in the form:

$$\frac{dm}{d\tau} = (\alpha P - bc)A \qquad (17)$$

During the de-aeration process (i.e. spraying) the term αP is very small in comparison with bc and, therefore, can be neglected without any appreciable error. Then equation (17) becomes:

$$\frac{dm}{d\tau} = -bcA \qquad (47)$$

or

$$\frac{dc}{d\tau} = -bc\,\frac{A}{V} \qquad (48)$$

Let c_1^*, c_2^*, c_3^* be the original concentrations in the water sample of carbon dioxide, oxygen and nitrogen respectively, and c_1, c_2, c_3 the corresponding concentrations at any stage of de-aeration.

Then:

$$\begin{aligned} c_1 &= c_1^* \exp\left(-b_1\frac{A}{V}\tau\right) \\ c_2 &= c_2^* \exp\left(-b_2\frac{A}{V}\tau\right) \qquad (49) \\ c_3 &= c_3^* \exp\left(-b_3\frac{A}{V}\tau\right) \end{aligned}$$

Let

$$\frac{A}{V}\tau = \gamma \qquad (50)$$

The total concentration of gas in the water sample at any moment will be:

$$c_1 + c_2 + c_3 = c_1^* \exp\left(-b_1\gamma\right) + c_2^* \exp\left(-b_2\gamma\right) + c_3^* \exp\left(-b_3\gamma\right) \quad \text{.....(51)}$$

If φ is the ratio of gas concentration at any moment to the saturated gas content, (Fig. 1), then:

$$\varphi = \frac{c_1 + c_2 + c_3}{c_1^* + c_2^* + c_3^*} = \frac{c_1^* \exp\left(-b_1\gamma\right)}{c_1^* + c_2^* + c_3^*} + \frac{c_2^* \exp\left(-b_2\gamma\right)}{c_1^* + c_2^* + c_3^*} + \frac{c_3^* \exp\left(-b_3\gamma\right)}{c_1^* + c_2^* + c_3^*} \quad \text{.....(52)}$$

If the water sample were saturated with air under mean atmospheric conditions it follows from the analysis of section 2.2 in the previous report[1] that:

$$\frac{c_1^*}{c_1^* + c_2^* + c_3^*} = 0.028, \quad \frac{c_2^*}{c_1^* + c_2^* + c_3^*} = 0.360, \quad \frac{c_3^*}{c_1^* + c_2^* + c_3^*} = 0.612$$

From the Table on page 13 of ref. (1):

$$b_1 = 0.152 \text{ cm/min}, \quad b_2 = 0.538 \text{ cm/min}, \quad b_3 = 0.546 \text{ cm/min},$$

Substituting these values in equation (51):

$$\varphi = 0.028 \exp(-0.152\gamma) + 0.360 \exp(-0.538\gamma) + 0.612 \exp(-0.546\gamma) \quad \text{.....(53)}$$

The values of φ for various values of γ are given in Table 1 and the variation of φ against γ is plotted in Fig. 2.

Now it has been found that in samples originally saturated with atmospheric air the amount of gases which is still in solution after the first spray is 4 per cent of the original amount. From Fig. 2 this corresponds to $\Delta\gamma = 6.4$; $\Delta\gamma$ is a constant of the apparatus.

It is obvious now that from Fig. 2 and the known value of $\Delta\gamma$ the amount of gases still in solution - after the spraying process - in samples of water of various values of the original gas content can be estimated. If ω is the ratio of the gas content after spraying (12 sprays) to the original gas content (which may be saturated or less than saturated), Fig. 1, then the results of this estimation are shown in Table 2, and Fig. 3.

3. ACCURACY OF MERL APPARATUS

According to the present analysis the error which results by assuming that the sample of water is completely degassed after the suitable number of sprays is not constant all over the range of gas content but increases with samples of water of low gas-content.

Figs. 4 and 5 correspond to Figs. 12 and 13 of ref. (1) respectively. The variation of the accuracy of the MERL method with $x_1 - x_2$ when the released gases are constrained in 1 cm^3 volume is shown in Fig. 4 and when the released gases are constrained in 2 cm^3 volume in Fig. 5. In these figures x_2 is taken to be 166 mm.

4. SIMPLIFICATION OF THE METHOD OF CALCULATING THE PARTIAL PRESSURE OF THE TOTAL GAS-CONTENT OF A SAMPLE

The pressure of the total gas-content of a sample of water if the gases are released and constrained in 1 cm^3 volume is given by equation (28):

$$p^* = x_1 - x_2 + (p_{a_1} - p_{a_2}) + 0.927\ (x'_2 - x'_1) + \Delta p_2 + \Delta p_3 \qquad (54)$$

Equation (43) can be written:

$$\frac{p_{a_1} - p_{a_2}}{p_0} = \varphi(p_0) = r \qquad (55)$$

r is plotted against p_0 in Fig. 6 where

$$p_0 = x_1 - 285 \qquad (56)$$

In the same figure the curve $\omega = f\ (p_0)$ is plotted, ω being the ratio of the amount of gases still in solution after the spraying to that originally dissolved in the sample of water.

Thus if x'_1, x_1 and x'_2, x_2 are determined for a given sample of water the pressure of the total gas content of the sample constrained in 1 cm^3 volume will be given by:

$$p^* = \left\{(x_1 - x_2)(1 + r) + 0.927\ (x'_2 - x'_1)\right\}\ (1 + \omega) \qquad (57)$$

5. CONCLUSIONS

The MERL air-content apparatus uses a spraying process under vacuum to extract the air from a water sample. A method has been described that enables the quantity of air left in the water after this spraying to be determined.

Although this analysis has been worked out for the MERL apparatus and is thus referred to in both reports, it applies equally well to other air-content apparatus of the extraction type (e.g. Van Slyke, Shal'nev, Kanellopoulos), which are all subject in a greater or lesser degree to these errors and corrections.

REFERENCES

1. KANELLOPOULOS, E.V. New method for measuring the gas content of water. *MERL Fluids Report* No 69. East Kilbride, Glasgow: Mechanical Engineering Research Laboratory, 1958.

2. WILLIAMS, E.E. The determination of dissolved air in water. *Lab. Pract.*, 1954, 7(3), 275-278.

LIST OF TABLES

LIST OF FIGURES

Distribution - Group 4 & 8.

TABLE.1. De-aeration of water.
Variation of φ with γ.

γ	$\exp(-b_1\gamma)$	$\exp(-b_2\gamma)$	$\exp(-b_3\gamma)$	100φ	(*) p' (mm Hg)
0	1	1	1	100	165
0.5	0.927	0.764	0.761	76.6	126.2
1.0	0.859	0.584	0.579	58.7	96.8
2.0	0.738	0.541	0.336	34.7	57.3
3.0	0.634	0.199	0.194	20.8	34.3
4.0	0.544	0.116	0.113	12.6	20.8
5.0	0.468	0.067 8	0.065 2	7.7	12.7
6.0	0.402	0.039 6	0.037 6	4.84	8.0
7.0	0.345	0.023 1	0.021 9	3.12	5.15
8.0	0.296	0.013 5	0.012 6	2.08	3.43
9.0	0.255	0.007 9	0.007 3	1.44	2.37
10.0	0.219	0.004 6	0.004 3	1.04	1.72
12.0	0.161	0.001 57	0.001 43	0.59	0.97
14.0	0.119	0.000 52	0.000 48	0.375	0.62
16.0	0.087 8	0.000 18	0.000 16	0.257	0.42
18.0	0.064 8	0.000 062	0.000 055	0.184	0.30
20.0	0.047 8	0.000 020	0.000 018	0.133	0.22

(*) p' is given by

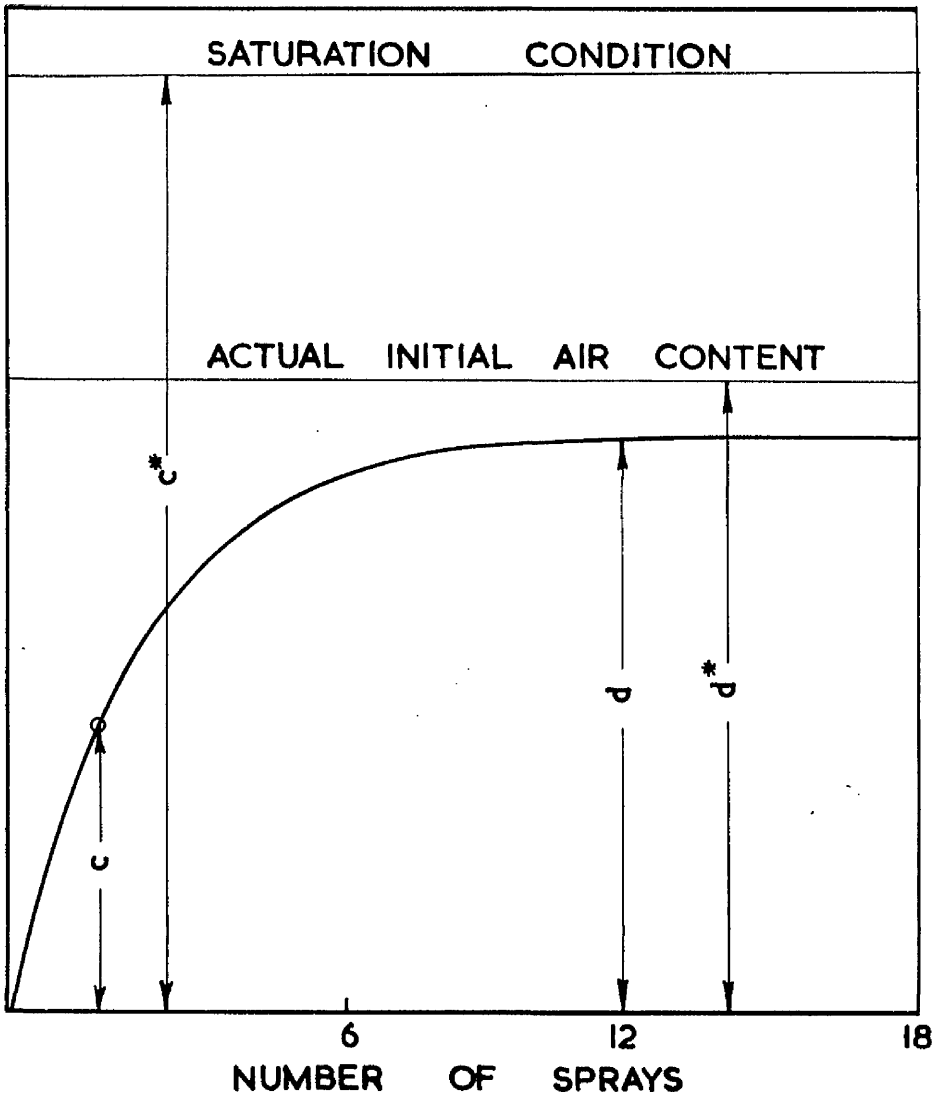
$$p' = (x_1 - x_2) + (p_{a_1} - p_{a_2}) + 0.927\ (x'_2 - x'_1)$$

TABLE 2. Amount of Gases remaining in Solution in the Sample of Water after Spraying.

$100\ \varphi$	p'	(*) $100\ [\varphi(\gamma) - \varphi(\gamma + 6.4)]$	$100\ \omega$
100	165	4.00	4.00
	150	3.60	4.00
80	130	3.25	4.05
70	115	2.95	4.20
60	100	2.65	4.40
50	80	2.30	4.60
40	65	1.95	4.85
30	50	1.60	5.35
20	33	1.20	6.00
10	16	0.80	8.00
5	8	0.54	11.00

(*)

φ is taken from equation (53).



$$\varphi = \frac{c}{c^*} \quad , \quad \omega = \frac{d}{d^*} \quad .$$

FIG. 1. DEFINITION OF φ AND ω

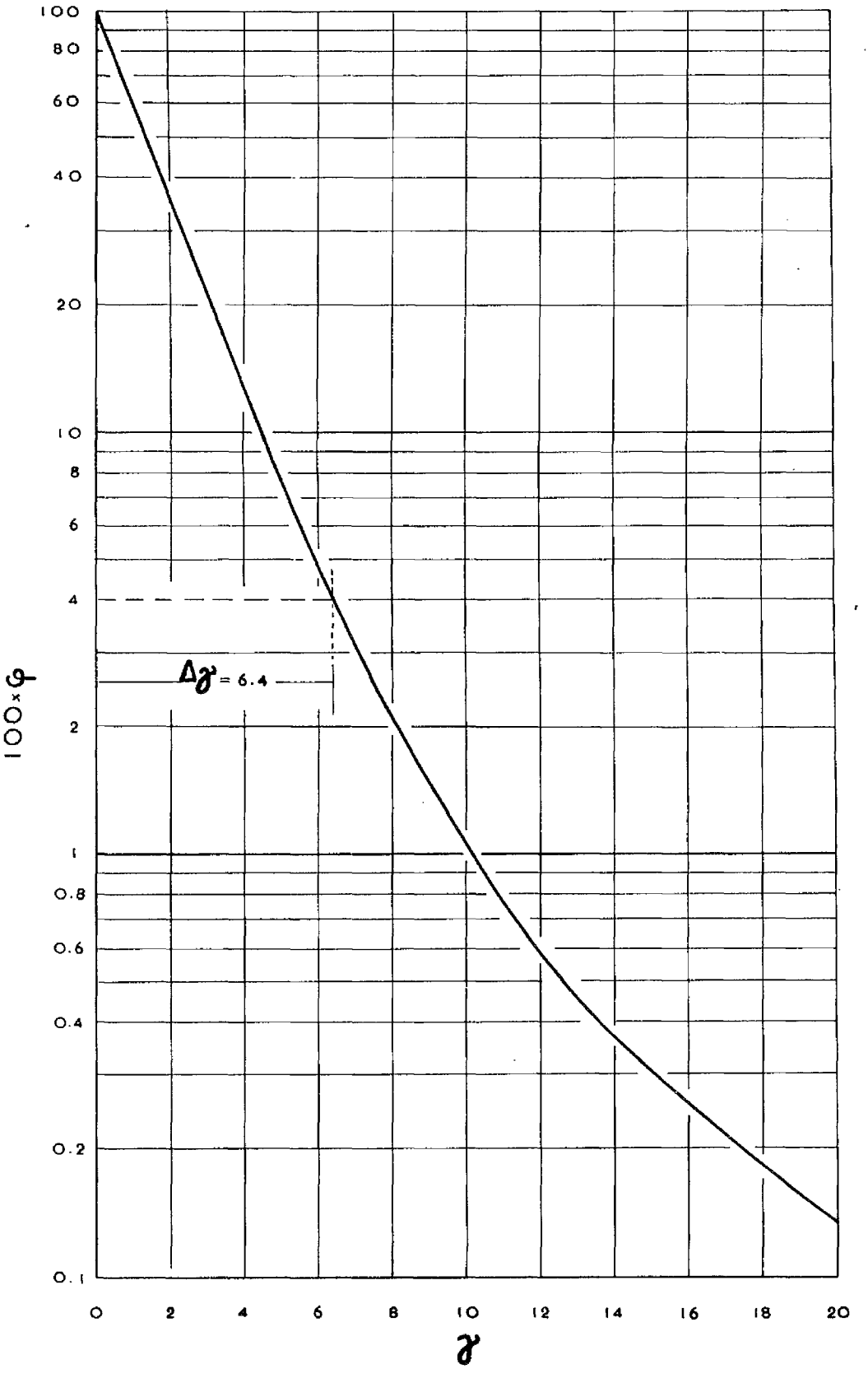


FIG. 2. VARIATION OF φ WITH γ

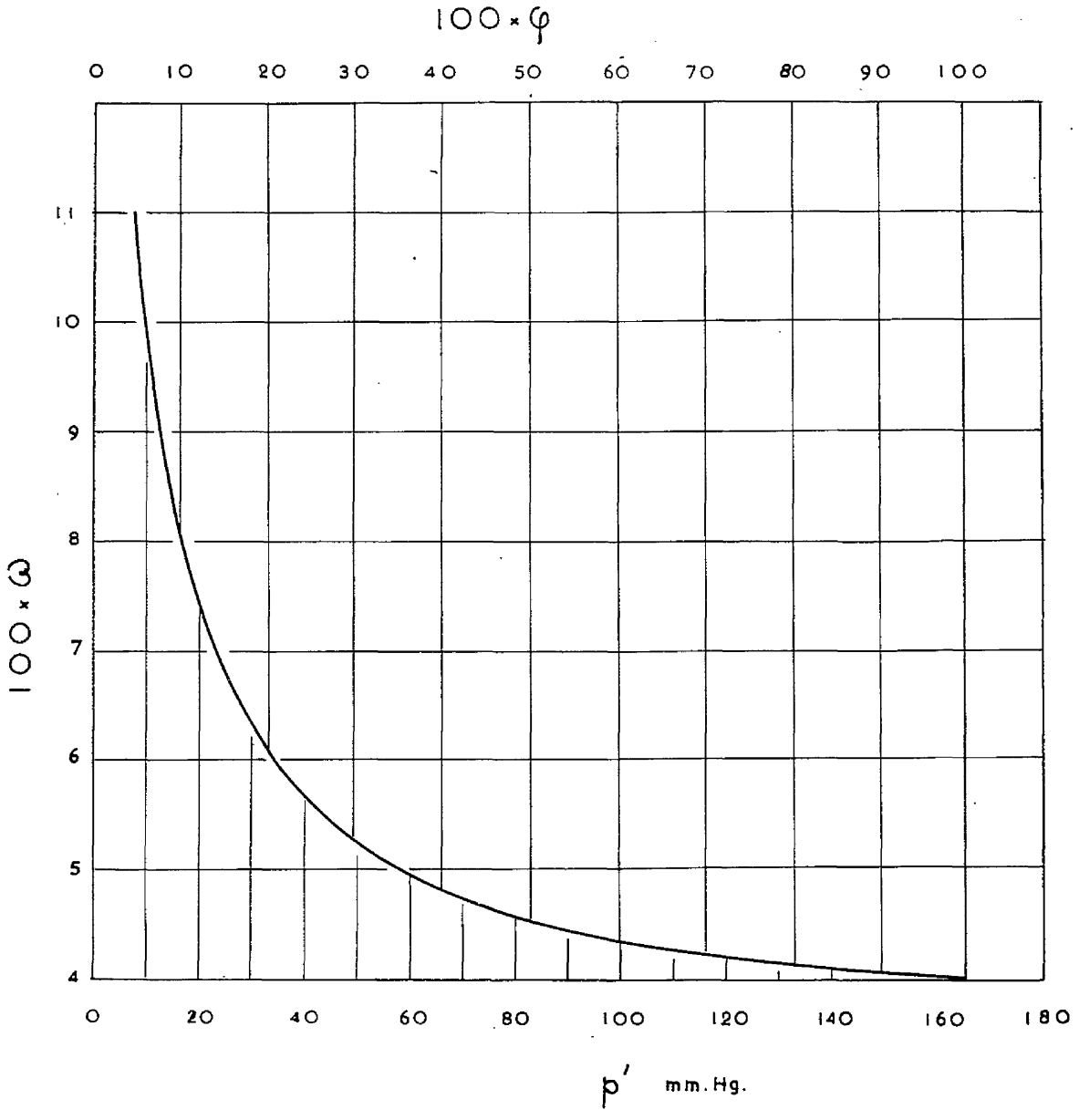


FIG. 3. VARIATION OF ω WITH p' AND φ

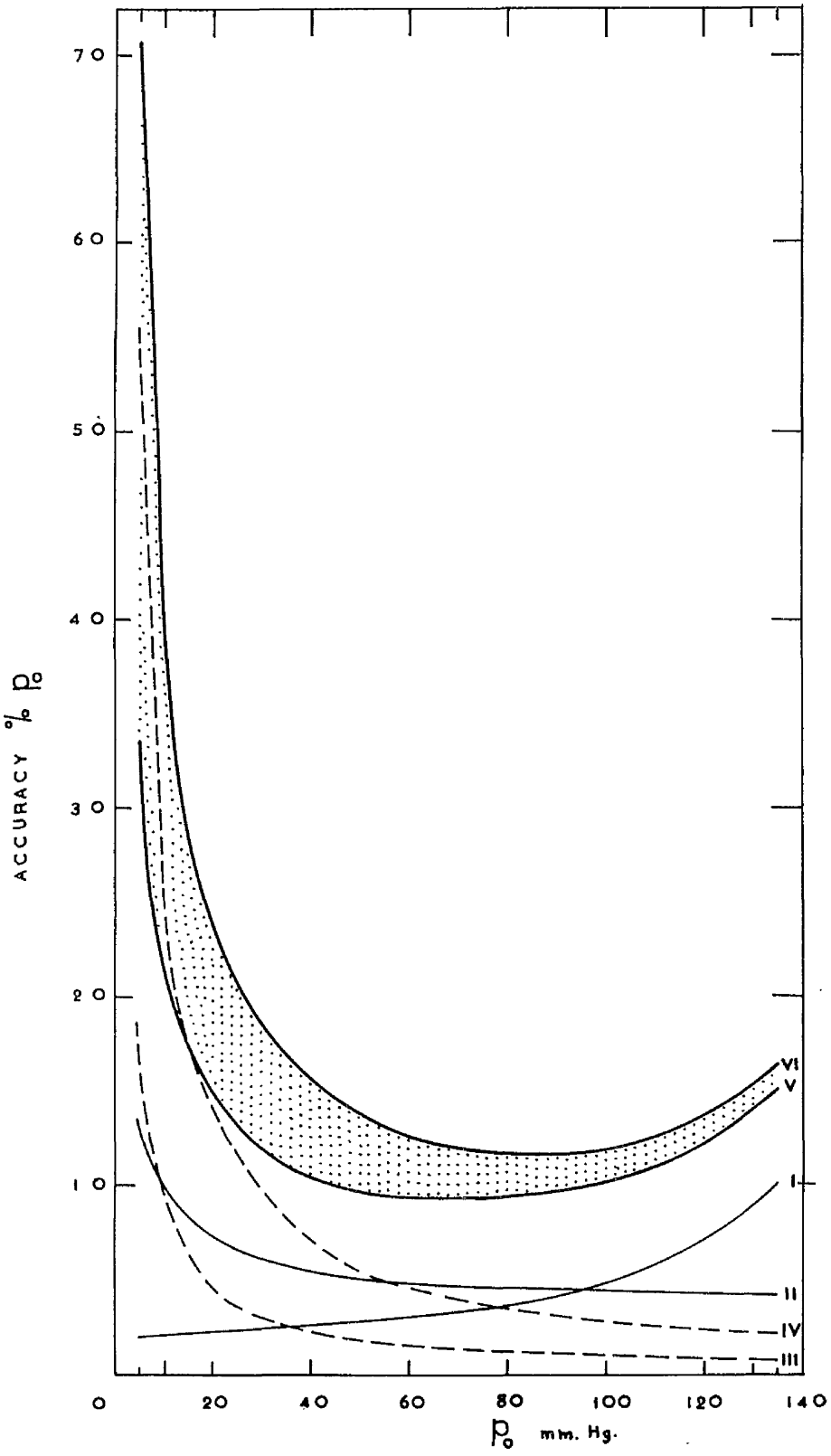


FIG. 4. ACCURACY OF MERL APPARATUS (GASES CONSTRAINED TO 1 cm^3)

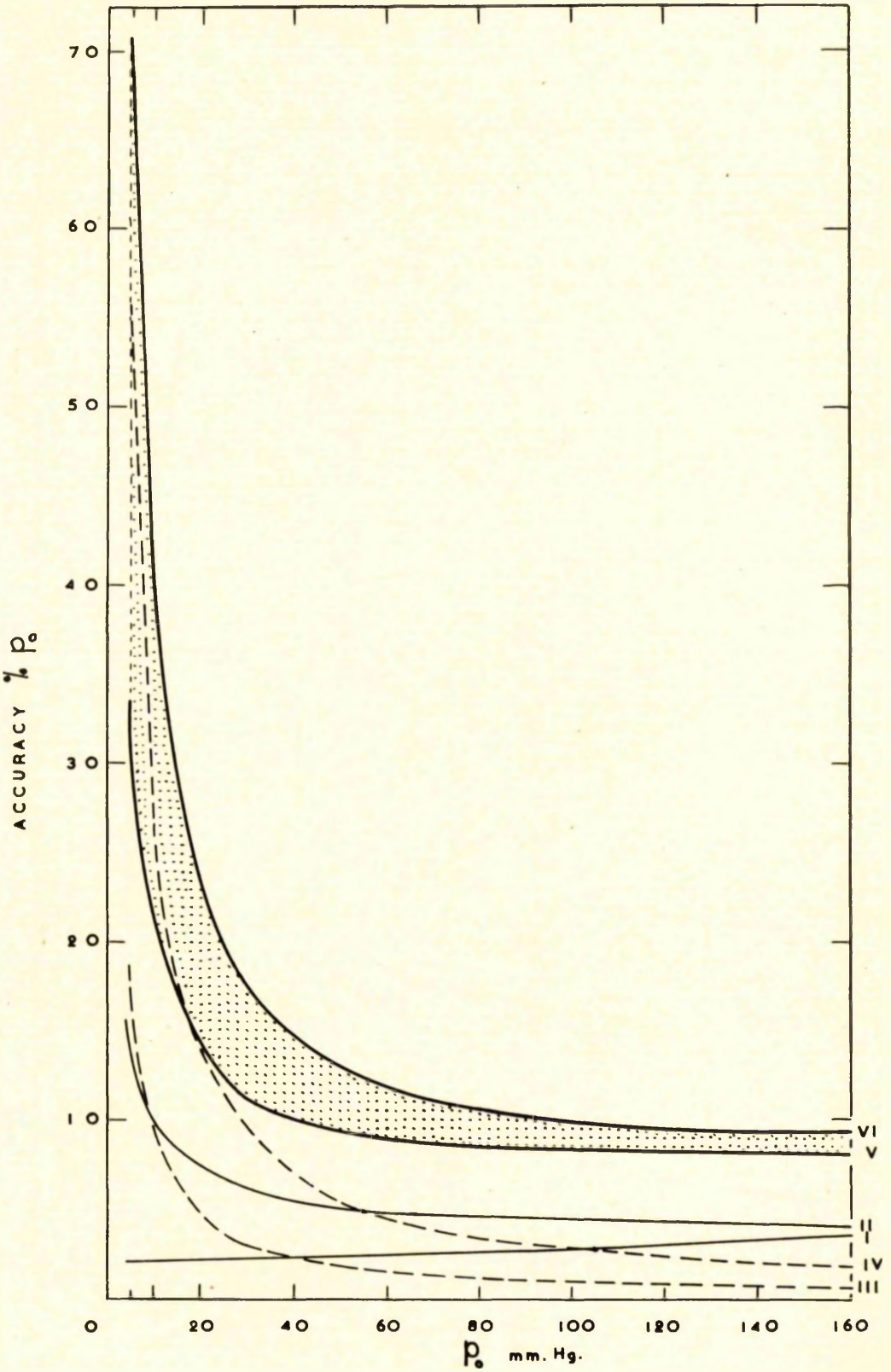


FIG. 5. ACCURACY OF MERL APPARATUS (GASES CONSTRAINED TO 2 cm^3)

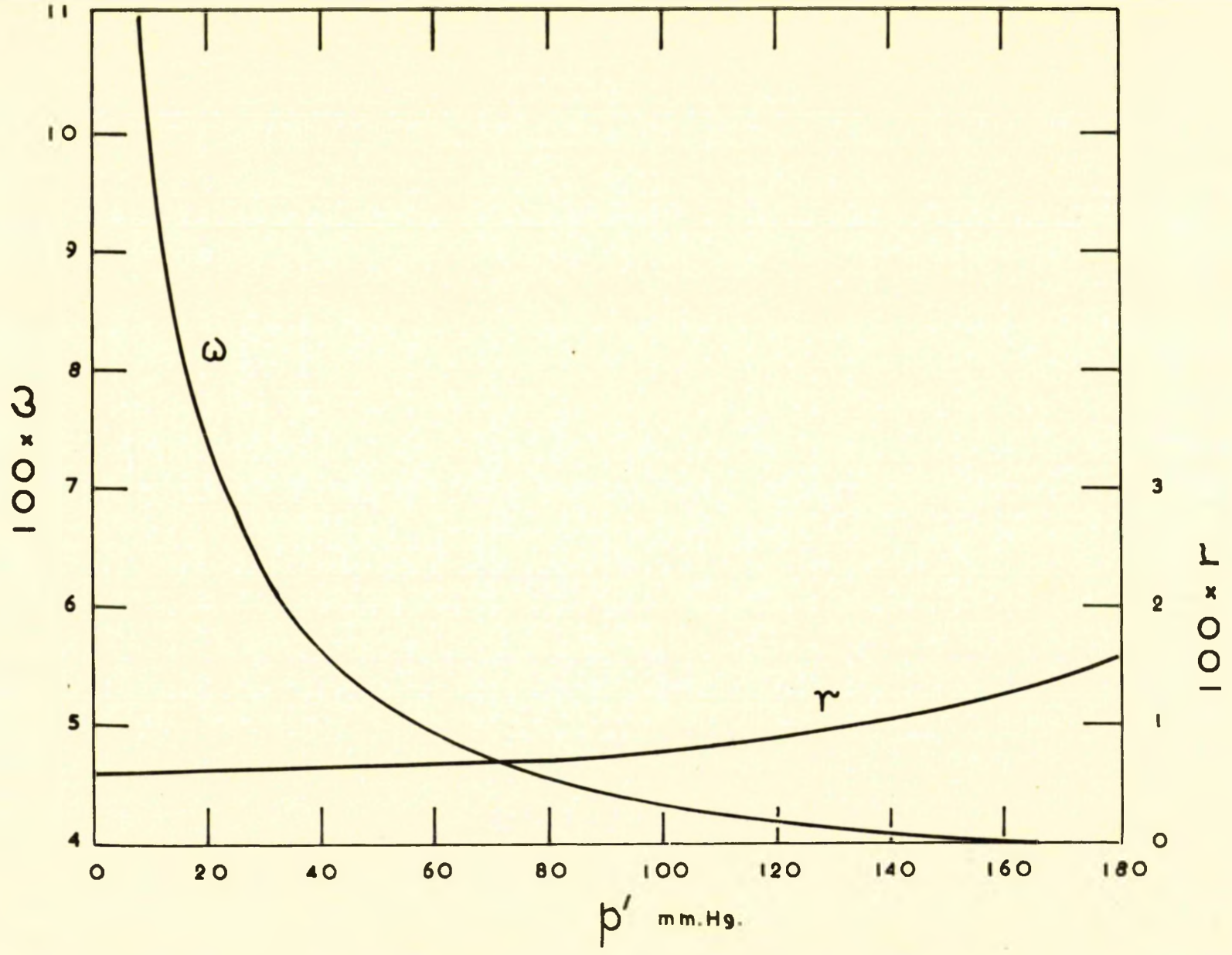


FIG. 6. VARIATION OF ω AND r WITH p'

MERL FLUIDS NOTE No 78

MECHANICAL ENGINEERING RESEARCH LABORATORY
FLUID MECHANICS DIVISION

Methods of Sampling Water for Measuring the Gas Content

E. V. KANELLOPOULOS

APPENDIX IV

March 1959

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DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

MECHANICAL ENGINEERING RESEARCH LABORATORY

METHODS OF SAMPLING WATER FOR MEASURING THE GAS CONTENT

by

E.V. Kanellopoulos, Dipl.Ing., M.I.M. and E.E.(Greece)
(University of Glasgow)

SUMMARY

An investigation is made into the effect of the sampling method on the accuracy of the determination of gas content. Two new methods for sampling water at sub-atmospheric pressures are described. The second appears to be a method which could be generally adopted for obtaining truly representative samples of water.

CONTENTS

1. INTRODUCTION

The accuracy of measuring the total gas content of water depends not only on the accuracy of the gas-content meter but also on the method of sampling the water. The problem of obtaining a truly representative sample raises difficulties when the pressure at the sampling point is lower than atmospheric. When the pressure at the sampling point is greater than atmospheric no difficulty arises because by exposing the end of tube (2) (Fig. 1) to the atmosphere a flow of water is established through the gas-content apparatus, due to the pressure difference $p_1 - p_2$.

Where $p_1 < p_{atm}$, there are two methods in use at present for applying the necessary pressure difference $p_1 - p_2$ for taking the sample. The first method consists of applying a vacuum at point (2) so that $p_2 < p_1$. In the second method the whole system is pressurised, before taking the sample, until the pressure at point (1) is brought above atmospheric. Both these methods, as shown later, have certain disadvantages and their use would result in abstracting not truly representative samples of water, as far as their gas content is concerned.

In the first method it is difficult to control the pressure difference $p_1 - p_2$ because p_1, may vary within wide limits depending on the conditions in the circuit. In cases of comparatively high gas contents, part of the gases dissolved in the sample will come out of solution and the measured gas content will be less than the real one by the amount of gases released during the sampling.

The factors which will affect the measurement of gas content in samples taken by this method are: the real gas content of the water in the vicinity of point (1), the pressure p_2, and the difference $p_1 - p_2$.

Let α_1 be the real gas content and α_2 the gas content which corresponds to the equilibrium condition (saturation) under static pressure p_2.

Then according to Henry's Law:

$$\alpha_2 = \alpha_s \frac{p_2}{p_{atm}}$$

Where α_s is the gas content of water saturated under atmospheric conditions and p_{atm} is the atmospheric pressure, the ratio $\frac{\alpha_1}{\alpha_2}$ represents the degree of supersaturation or undersaturation of the sample. As $\frac{\alpha_1}{\alpha_2}$ is increasing, the amount of gases coming out of solution during the sampling process will increase. For the same value of the ratio $\frac{\alpha_1}{\alpha_2}$, the greater the difference $(p_1 - p_2)$ the higher the velocity of flow through the sampling system and the shorter the time during which each part of the sample is exposed to the supersaturation condition i.e. the smaller the amount of gases released during the sampling. On the other hand the greater the value of α_1 the greater is the rate of deaeration.

The second method (pressurisation of the circuit) will give representative samples only in the absence of free surfaces of water or in cases of comparatively high gas contents. In the absence of free surfaces of water pressurisation does not affect the total gas content of the water. However, if the tunnel has a comparatively large ratio of A/V where A is the area of the free surface and V the volume of water in the tunnel, pressurisation will result in increasing the total gas content and the measured gas content will be higher than the real one. This difference is negligible when the gas content is high but it may become appreciable in cases of very low gas contents. It will depend also on the time necessary for the pressurisation and on the time for obtaining the sample of water.

Because of their disadvantages neither of the two methods mentioned above may be adopted generally as reliable methods of taking samples of water under all conditions of pressure and gas content of the water in the circuit.

In connection with experiments on the influence of the gas content on the inception of cavitation in a small centrifugal pump circuit, two new methods (A and B) have been developed for sampling water. These methods eliminate the disadvantages of the above methods and enable a truly representative sample to be taken.

2. METHOD A

2.1 Description of Apparatus

A glass reservoir R_1 (Fig. 2) of about 400 cm^3 capacity is connected through cocks C_1 and C_2 across the vacuum valve V in the circuit piping. Cock C_3 connects R_1 to the mercury reservoir R_2, while cock C_4 connects R_1 with the gas content apparatus.

2.2 Principle of Operation

The flow in the pipe causes a pressure difference across valve V. If cocks C_1 and C_2 are open while C_3 and C_4 are closed (with the level of mercury in R_1 at the centre line of cock C_3), water will run through the reservoir R_1 in the direction from C_1 to C_2. The water flows through the reservoir R_1 until it is certain that the water in R_1 has been renewed. Then cocks C_1 and C_2 are closed and after opening cock C_3 the mercury reservoir R_2 is raised up to a fixed level. By this operation the water in R_1 is pressurised to a pressure higher than atmospheric. If cock C_4 is opened the water will start running through tube (1), over the top of cock C of the gas content apparatus and through tube (2) to the vessel R_3. After sufficient water has run into vessel R_3 cock C is set to connect R_1 with the gas content apparatus and by raising or lowering R_2 the required 10 cm^3 sample of water is taken. C_4 is then closed, R_2 is lowered and C_2 opened until the reservoir R_1 is filled with water. The apparatus is then ready for the next test.

2.3 Calibration of the Sampling Apparatus

The pressure difference across the valve V and consequently the velocity of flow through the reservoir R_1 will be a function of the rate of flow in the main circuit. Thus, the time which is needed to renew the water in reservoir R_1 depends on the rate of flow through the main circuit. The time necessary for

complete renewal of the water in R_1, at different rates of flow was found by filling R_1 from R_3 with a fixed-strength dye solution. The time was then the time necessary to clear the dye solution in R_1. Table 1 gives the times measured for various speeds of the circulating pump and with the flow-regulating valve of the circuit fully open.

By filling the tube (1) with dye solution from R_3 the amount of water required to be run back through this tube to clear out the coloured solution was measured. This was done by marking the level of mercury on the wall of the reservoir R_1. The mark indicated the lowest level of mercury above which a representative sample of water could be obtained in the gas content apparatus.

The advantage of this method is that a truly representative sample of water is taken under any condition of static pressure in the circuit. However the method has the following disadvantages. When the rate of flow through the main circuit is very small the time necessary to renew the water becomes very large and during this period the conditions of the circuit as regards the total gas content may alter greatly. It is not therefore possible to take a sample of water by this method while the circuit is static. Another disadvantage is that after each measurement of gas content about 300 cm^3 of water are lost from the tunnel. This loss in water becomes appreciable in a small circuit after a large number of gas-content measurements.

3. METHOD B

In another cavitation circuit at present being designed only one tank instead of two is to be used. If method A was used for sampling the water a valve would have to be placed in the suction pipe of the centrifugal pump. Also the volume of water in the new circuit will be about half of the circuit of Fig. 2 and the loss in water after a large number of gas-content measurements would be more noticeable.

Method B overcomes the disadvantages of Method A and may be used under any circuit conditions and without loss of water.

3.1 Description of Apparatus

The apparatus used with method B is shown in Fig. 3.

R_1 and R_2 are two thick-walled glass reservoirs of 350 cm^3 and 450 cm^3 capacity respectively which jointly contain about 400 cm^3 of mercury. Each of the glass reservoirs has on its top a 2-way high vacuum cock. A and B are two pieces of copper tubing bent to form right angles and brazed on to the tank wall. The connections Aa, be, fd, cB and the connection between R_1, R_2 are made with polythene tubing.

3.2 Principle of Operation

If cock C_1 is open to a and cock C_2 to c the pressure in R_1 is equal to that in R_2 and the levels of mercury in the two reservoirs are in the same horizontal plane under any condition of operation in the circuit.

By lowering slowly the reservoir R_2 mercury starts running from R_1 to R_2 and R_1 is gradually filled with water. Next C_1 is open to b and C_2 to d and the reservoir R_2 is raised, forcing the water from R_1 to flow through the top of the gas-content apparatus into the reservoir R_2. After some water has been transferred from R_1 to R_2 cock C_3 is opened to c to connect the line from R_1 with the gas-content apparatus. Then by adjusting the level of R_2 the 10 cm^3 of the sample can be drawn into the gas-content apparatus.

To remove the water which remains in the tubings Aa and be from the previous sampling, just before taking the new sample, sufficient water is introduced into R_1 which is immediately expelled. The operations for taking the sample as described above are then repeated.

4. CONCLUSIONS

Two new methods of sampling sub-atmospheric or pressurised water have been devised. Method B is to be preferred and has the following advantages:-

a. The device consists of a closed circuit and so there is no loss of water.

b. Because its operation is based on a differential method it can be used under any conditions of pressure in the main circuit. The upper limit in pressure is the safety pressure of the glass reservoirs R_1, R_2.

c. The time necessary for taking the sample is independent of the pressure in the circuit and of the rate of flow through it and is much smaller (about 1 minute) than the average time necessary with method A.

Reduction of the time of sampling is a most important necessity because, depending on the conditions of the amount of dissolved gases and the pressure in the circuit, the gas content may change greatly in a period of only a few minutes.

ACKNOWLEDGEMENT

The work described was undertaken in the Department of Aeronautics and Fluid Mechanics of the University of Glasgow under the guidance of Prof. W.J. Duncan and Dr. A.S. Thom, using equipment loaned by the Mechanical Engineering Research Laboratory. It is published by permission of the Dean of the Faculty of Engineering, University of Glasgow.

Distribution: Groups 4 and 8.

LIST OF FIGURES

TABLE 1

Speed of circulating pump REV/MIN	Average measured times for renewing the water in Reservoir R_1 MIN
1000-1500	3.5
1500-2000	2.5
2000-2500	2.0
2500-3000	1.5

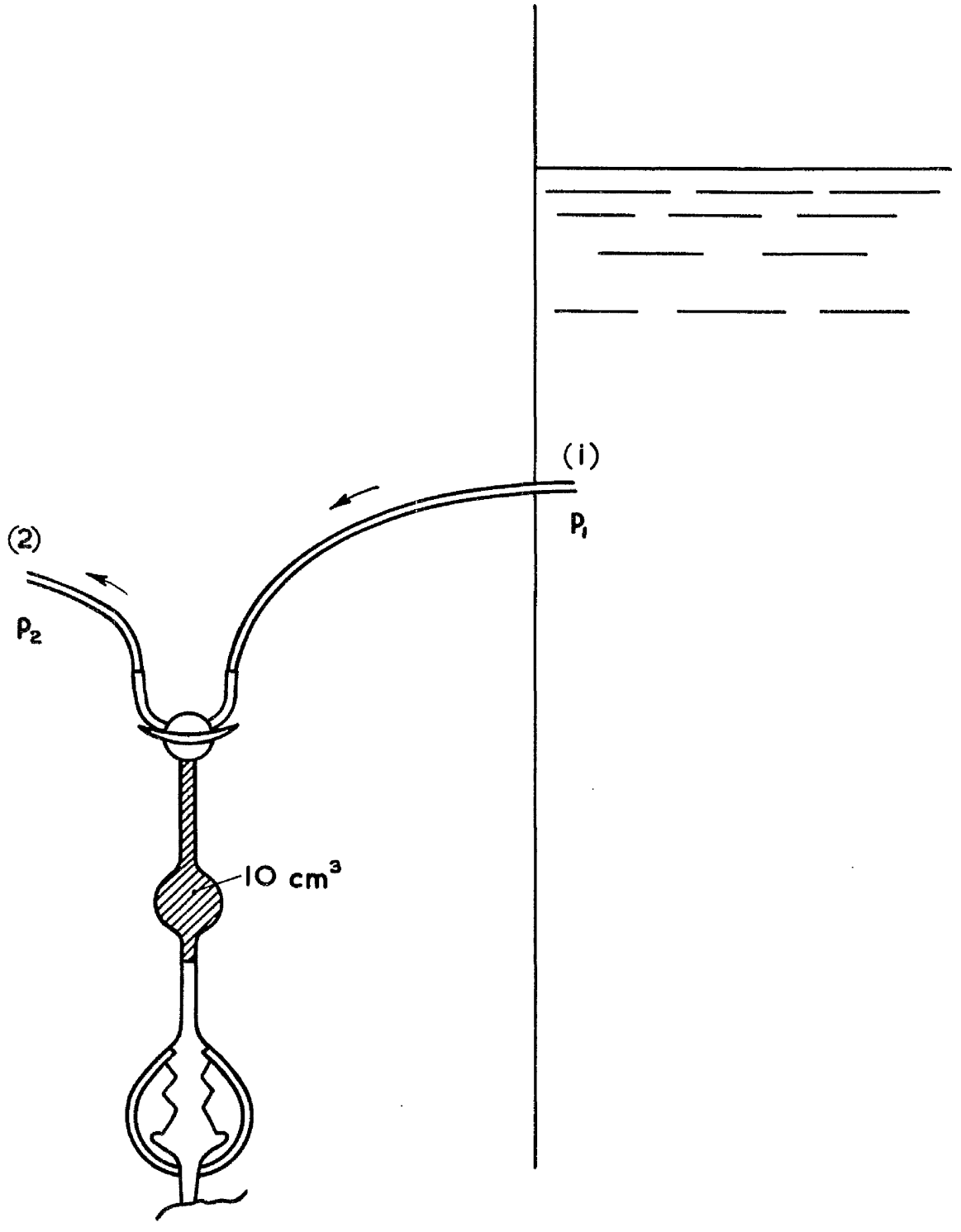

FIG. 1. SAMPLING METHOD – p_1 ABOVE ATMOSPHERIC PRESSURE

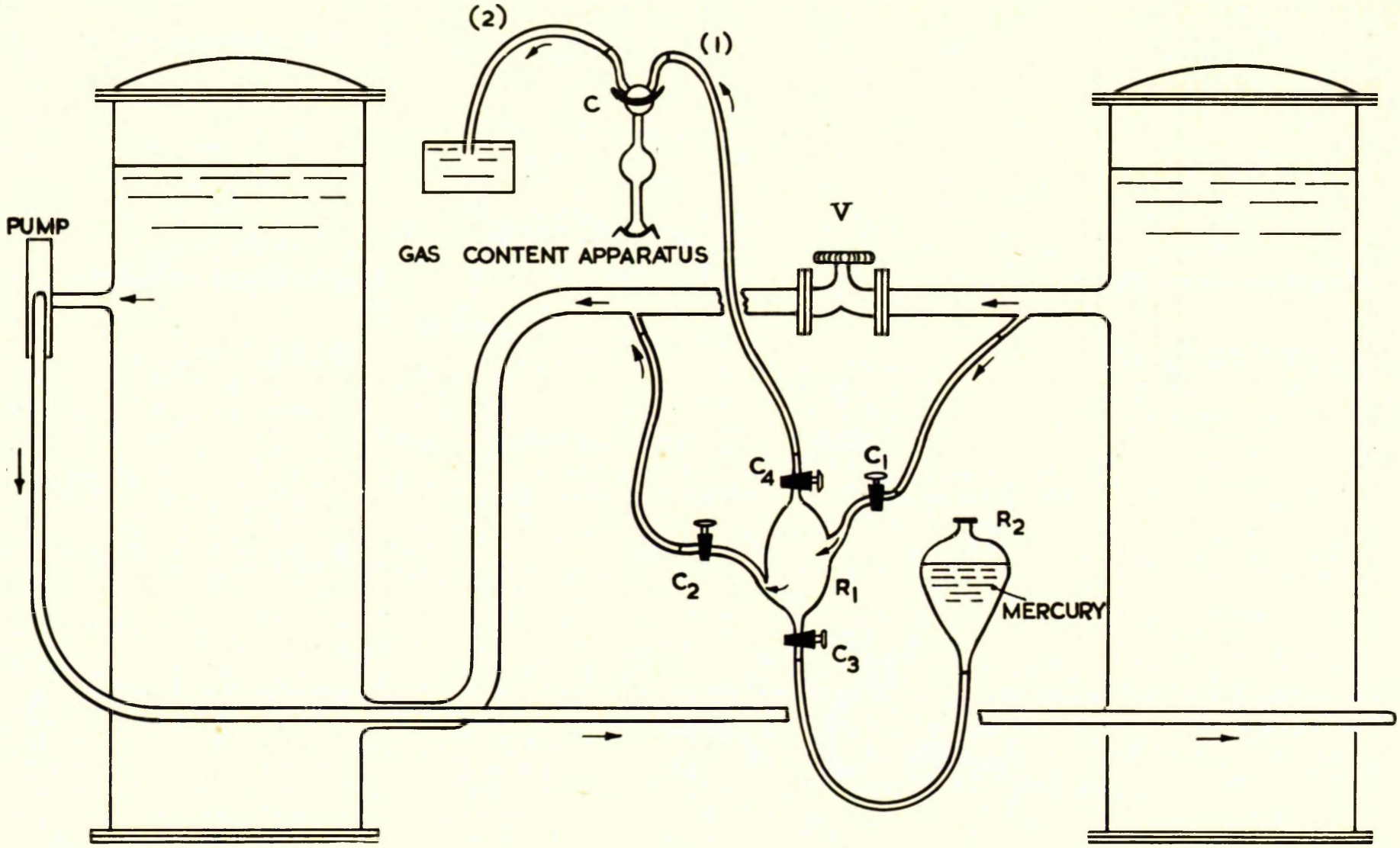

FIG. 2. SAMPLING METHOD A, p_1 LESS THAN ATMOSPHERIC PRESSURE

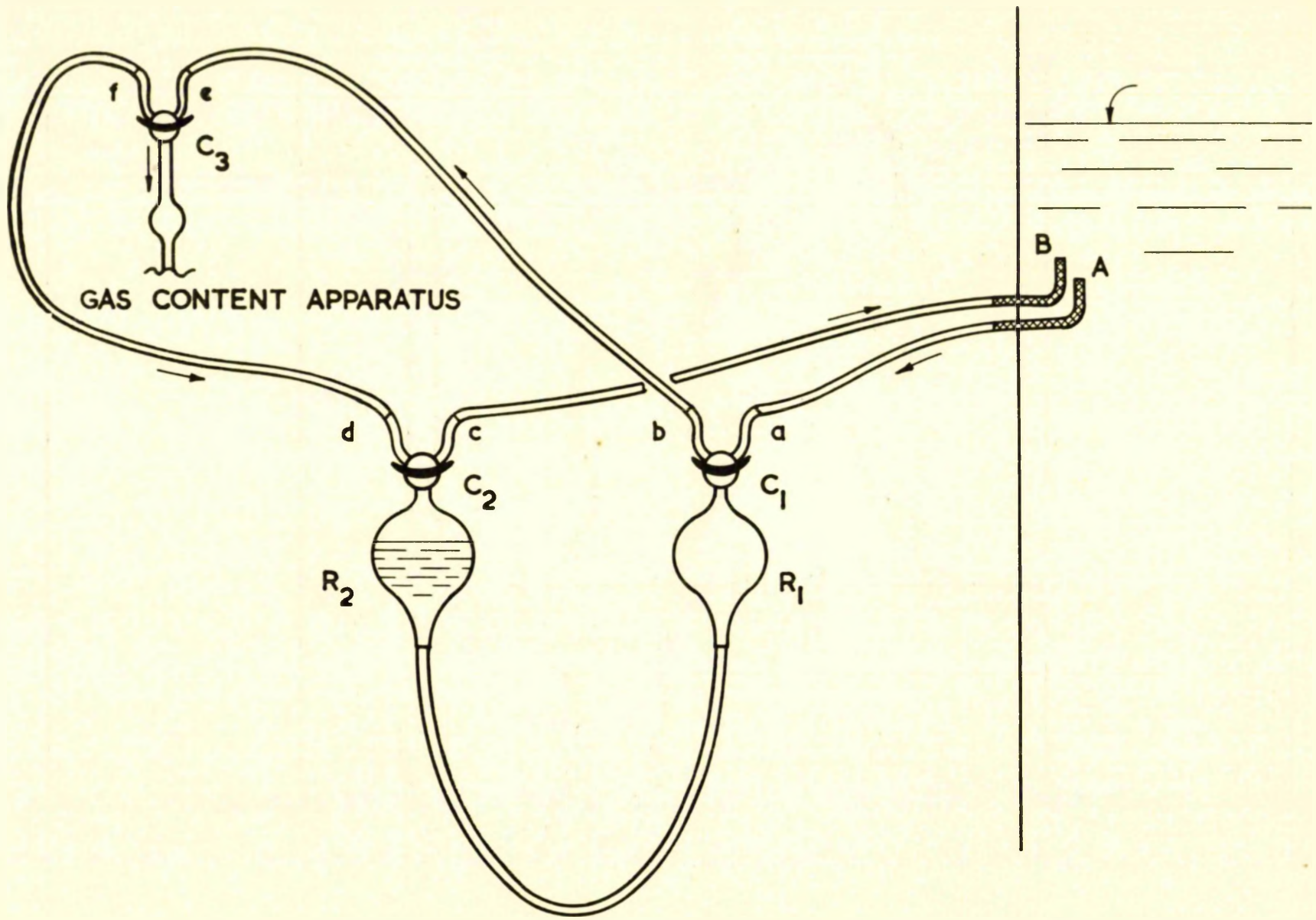

FIG. 3. SAMPLING METHOD B, p_1 LESS THAN ATMOSPHERIC PRESSURE

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FLUID MECHANICS DIVISION

Variation of Total Gas Content in a Small Cavitation Circuit

E. V. KANELLOPOULOS

APPENDIX V

March 1959

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DIRECTOR, M.E.R.L., EAST KILBRIDE, GLASGOW

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

MECHANICAL ENGINEERING RESEARCH LABORATORY

VARIATION OF TOTAL GAS CONTENT IN A SMALL CAVITATION CIRCUIT

by

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(University of Glasgow)

SUMMARY

A theoretical and experimental investigation has been made into the factors affecting the de-aeration of a small closed circuit cavitation rig.

Commencing with saturated water, the rate of de-aeration was measured under a high vacuum at different pump speeds (circulation speeds). It was found that the air content could be reduced by 50% in ten minutes, and that the rate of de-aeration depended mainly on pump speed (circulation speed). Because of the rapid de-aeration the range of gas contents available for test purposes was limited. It is suggested that to increase this range a more soluble gas, carbon dioxide, should be used.

The actual water-gas interface area (including bubbles and cavitation zones) is calculated and is found to vary from 5 (no flow) to 50 (full flow) times the free surface areas in the tanks.

CONTENTS

NOTATION

Symbol	Definition
A	Total gas-water interface area
A_0	Water surface area in the tanks
a	Entrance coefficient of gas
b	Exit coefficient of gas
b_0	Exit coefficient of a single homogenous gas
b_a	Exit coefficient of atmospheric air
b_1	Exit coefficient of CO_2
b_2	Exit coefficient of O_2
b_3	Exit coefficient of N_2
C	Concentration of one gas in the liquid at time t
C^*	Concentration of one gas in the liquid at time $t = 0$
$C_0{}^t$	Concentration of total dissolved gases at time t
$C_0{}^0$	Concentration of total dissolved gases at time $t = 0$
$C_1{}^0$	Concentration of CO_2 at time t
$C_2{}^0$	Concentration of O_2 at time t
$C_3{}^0$	Concentration of N_2 at time t
D	Diameter of the tanks
h	Height of water column in the tanks
P	Absolute pressure
p_i	Absolute pressure in pump discharge
p_x	Partial pressure of the gases in the tanks
p_{atm}	Atmospheric pressure
t	Time
V	Volume of water in the circuit

Symbol	Definition
α	Total gas content (cm^3/litre) at time t
α_0	Total gas content (cm^3/litre) at time $t = 0$
α^*	Total gas content saturated under atmospheric conditions
α_x	Total gas content saturated under partial pressure p_x
α_i	Total gas content saturated under partial pressure p_i
α_t	Total gas content at time t
λ	$\frac{b\ A}{V}$
λ_0	$\frac{b_a\ A_0}{V}$
γ	$\frac{A_0}{V}\ t$
ε	$\frac{aAP}{V}$
μ	$\frac{\varepsilon}{\lambda\ c^*}$

1. INTRODUCTION

Preliminary tests on the influence of total gas content on the inception of cavitation in a small centrifugal pump indicated that the de-aeration of the water took place much more quickly than was expected.

The total time necessary for adjusting the circuit to the desired conditions, taking the sample of water, and measuring the gas content, was never less than 10 minutes. In such an interval of time it was noticed that the gas content could drop to 50 per cent of its original value, depending on the conditions of gas content, pressure and rate of flow in the circuit. This imposes some limitations on the range of gas content in which experiments on cavitation may be carried out.

To prepare a suitable research programme which would have as short an experimental time as possible, it was thought that the actual de-aeration of the water in the small cavitation circuit (Fig. 1) should be systematically investigated.

2. PROCEDURE

The de-aeration of the water in the circuit was tested for various speeds of the centrifugal pump. In all these tests the flow-regulating valve was kept constantly at the fully open position (maximum flow).

The method used for taking the samples of water for measuring the gas content was the method A[1]. The gas contents were measured with the gas content apparatus described in [2] and were corrected according to the method described in [2] and [3].

The water used was tap water which was renewed after each series of tests. After filling with fresh tap water, the circuit was left open to the atmosphere for about 24 hours. During this period of time the circulating pump was run at 2000 rev/min twice for about 10 minutes each time in order to assist the establishment of an equilibrium state between dissolved gas content and atmospheric air. (Fresh tap water is usually supersaturated).

Before the start of each series of tests, the vacuum pump was run. When the ultimate vacuum was nearly reached the circulating pump was set to operate at 2000 rev/min for the period of time necessary to take a sample of water (about 2 minutes). It was found that at this stage the gas content of the water was nearly the same for each series of tests.

Immediately after taking the sample of water the circulating pump was adjusted to operate at the desired speed which was kept as nearly as possible constant for each series of tests. Because at the beginning of each run the de-aeration was very rapid, measurements of gas content had to be taken as frequently as possible. For this reason a new sample was taken while the gas content of the previous sample was being measured. However, it was not possible to measure the gas content at intervals of time smaller than 5 minutes.

As the rate of de-aeration was continuously decreasing with time the frequency of gas content measurements was gradually reduced.

The de-aeration of the circuit was tested for centrifugal pump speeds of 2800, 2500, 2000, 1500 and 1000 rev/min and with the pump nominally stopped. This run will be called: test at 0 rev/min. In this test the centrifugal pump was set to operate at 1000 rev/min for 35 minutes each time, in order to take samples of water for the gas content measurements. Having plotted the de-aeration curve of the circuit for 1000 rev/min against time the experimental results for the 0 rev/min run were corrected to the right values.

3. EXPERIMENTAL RESULTS

The experimental results for the de-aeration of the circuit with the pump operating at 2000 rev/min have been plotted in Fig. 2.

In this graph the gas content is expressed as the percentage ratio of the gas content at a given time t ($t = 0$ at the beginning of de-aeration) to that at the beginning of each test run. The initial value was the same for all the series of tests and was 19.5 cm^3 of gas (referred to NTP) per litre of water.

The pressure in the gaseous space of the circuit above the water was not absolutely constant during each series of tests; it decreased slightly towards the end of each test run. In addition the mean pressure for the various runs could not be kept at exactly the same magnitude.

However, the differences found in the rates of de-aeration for the various tests are very large and it is unreasonable to attribute such large differences to the small variations in the pressure of de-aeration.

The mean pressures under which the de-aeration took place in the various test runs are given in Table 1.

4. MATHEMATICAL TREATMENT OF RESULTS

4.1 Introduction

The variation in concentration of a dissolved gas with time for a continuous process of de-aeration under constant partial pressure in the gaseous space is given by equation (18) of ref. [4].

$$\frac{C}{C^*} = e^{-\lambda t} + \frac{\varepsilon}{\lambda C^*}\left(1 - e^{-\lambda t}\right) \qquad (1)$$

where

C is the concentration at time t

C^* is the concentration at time $t = 0$

$\lambda = b\,\frac{A}{V}$

$\varepsilon = \frac{aAP}{V}$

A = total gas-water interface area

V = volume of water in the circuit

and a and b are the coefficients of entrance and exit of the gas respectively.

Equation (1) is obtained by integration of the differential equation:

$$\frac{dC}{dt} = \left(aP - bC\right) \frac{A}{V} \qquad (2)$$

under the following assumptions:

(i) the mixing of water is perfect

(ii) one gas only is present (it is applied to each gas individually)

(iii) P is constant

(iv) $\frac{A}{V}$ is a constant of the circuit.

None of the above assumptions is strictly fulfilled by the water of the circuit because:

The mixing of the water may not be perfect in the series of tests at low speeds of the centrifugal pump.

There is not only one gas but a mixture of at least three gases (N_2, O_2, CO_2), the composition of which in both the dissolved and released state changes with time (i.e. as the gas content of the water is reduced).

The total pressure in the gaseous space above the water changes slightly with time and consequently the partial pressures of the different gaseous constituents of the mixture also vary. In addition variation in the total dissolved gas content results in variation in the composition of the gaseous mixture released from the solution.

In the ratio $\frac{A}{V}$, V is nearly constant (it is reduced slightly each time by the amount of water drawn by the sampling apparatus). A is the sum of the area of the free surfaces of the two tanks (which is constant), the area of the interfaces of the cavitation zones with water, the total area of the surface of the nuclei content and that of the travelling bubbles which are formed after the collapsing of the cavitation cavities. Thus A largely depends on the cavitation characteristics of the circuit and under the same conditions of pressure and rate of flow, A will decrease as the gas content of the water is decreased.

However, in spite of all these deviations from the imposed simplified assumptions an equation of the form of equation (1) may quite satisfactorily describe the de-aeration of the circuit for the various speeds tested. It remains to calculate the "time coefficient" λ and the dimensionless quantity ε which we shall call μ for each of the λC^* selected speeds of the pump.

4.2 Determination of λ and μ

As an example for calculating λ and μ we shall consider the de-aeration of the circuit for 2000 rev/min of the centrifugal pump.

In equation (1) we can substitute for the ratio C/C^* the equivalent ratio α/α_0 where

α is the total gas content (cm^3/litre) at time t

and α_0 is the total gas content (cm^3/litre) at time $t = 0$

(In the present tests α_0 is, as has been mentioned, constant and equal to 19.5 cm^3/litre).

Substituting $\frac{\alpha}{\alpha_0}$ for $\frac{C}{C^*}$ and because

$$\frac{\varepsilon}{\lambda C^*} = \mu \qquad \text{.....(3)}$$

$$\frac{\alpha}{\alpha_0} = e^{-\lambda t} + \mu \left(1 - e^{-\lambda t}\right) \qquad \text{.....(4)}$$

Now from the experimental curve for the de-aeration at 2000 rev/min we have that

$$\left.\begin{aligned} &\frac{\alpha}{\alpha_0} = 0.620 \text{ for } t = 9.5 \text{ min} \\ \text{and} \quad &\frac{\alpha}{\alpha_0} = 0.372 \text{ for } t = 35 \text{ min} \end{aligned}\right\} \qquad \text{.....(5)}$$

Substituting the values of $\frac{\alpha}{\alpha_0}$ and t from (5) in (4) the following pair of equations is obtained:

$$0.620 = e^{-9.5\lambda} + \mu \left(1 - e^{-9.5\lambda}\right) \qquad \text{.....(6a)}$$

$$0.372 = e^{-35\lambda} + \mu \left(1 - e^{-35\lambda}\right) \qquad \text{.....(6b)}$$

From equation (6a)

$$\mu = \frac{0.620 - e^{-9.5\lambda}}{1 - e^{-9.5\lambda}} \qquad \text{.....(7a)}$$

and from (6b)

$$\mu = \frac{0.372 - e^{-35\lambda}}{1 - e^{-35\lambda}} \qquad \text{.....(7b)}$$

In Fig. 3 the variation of μ with λ is plotted from both equations (7a) and (7b).

The intersection of these two curves gives the solution to the pair of equations (7a) and (7b). From this figure we have

$$\left.\begin{aligned} \lambda &= 0.09 \\ \text{and} \quad \mu &= 0.34 \end{aligned}\right\} \qquad \text{.....(8)}$$

Thus the equation for the de-aeration curve of the circuit with the centrifugal pump operating at 2000 rev/min is

$$\frac{\alpha}{\alpha_0} = e^{-0.09t} + 0.34\left(1 - e^{-0.09t}\right) \qquad \text{.....(9)}$$

where t is given in minutes.

The same procedure was used to calculate λ and μ for the other speeds of the pump. The results have been tabulated in Table 2.

The de-aeration curves defined by equation (4) and Table 2 have been plotted in Fig. 2.

From this figure good agreement is evident between the experimental and theoretical curves for the de-aeration of the circuit.

5. ESTIMATION OF THE WATER-GAS INTERFACE AREA

5.1 Assumptions

The total area of the water-gas interface has been symbolized by A and its meaning has been explained in section 4.1.

To estimate A we shall try to find the change in dissolved gas content with time of de-aeration, under the hypothetical assumption that there are no water-gas interfaces in the body of the water in the circuit and that the only gas-water interface is the area of the free surfaces of the water in the two tanks (Fig. 1). In addition we shall assume that the pressure in the spaces above the water is equal to the vapour pressure i.e. that the partial pressures of the gases are zero.

If A_0 represents the area of the surfaces of water in the two tanks then:

$$\frac{A_0}{V} = \frac{2\,\frac{\pi}{4}D^2}{2\,\frac{\pi}{4}D^2 h} = \frac{1}{h}$$

neglecting the small volume of water in the pipes where

D is the diameter of each of the two tanks
and h is the height of water column in either of the two tanks

$h \simeq 5$ ft = 152 cm

and

$$\frac{A_o}{V} = \frac{1}{152}/\text{cm} \qquad (10)$$

The change in the total gas concentration for a continuous process of de-aeration under the same assumptions on which the present analysis is based is given by equation (9) of Ref. 4

$$\frac{C_o^t}{C_o^o} = \frac{C_1^o}{C_o^o} e^{-b_1\gamma} + \frac{C_2^o}{C_o^o} e^{-b_2\gamma} + \frac{C_3^o}{C_o^o} e^{-b_3\gamma} \qquad (11)$$

where

C_o^t is the total dissolved gaseous concentrations at time t
C_o^o is the total dissolved gaseous concentrations at time $t = o$
C_1^o, C_2^o, C_3^o are the concentrations of dissolved CO_2, O_2, N_2 respectively at time t
b_1, b_2, b_3 are the coefficients of exit of CO_2, O_2 and N_2 respectively

and $$\gamma = \frac{A_o}{V} t \qquad (12)$$

If now we make an approximation by assuming that atmospheric air is a homogeneous single gas with coefficient of exit b_o and if we substitute for the ratio of concentrations the ratio of gas contents at time t and time $t = o$, equation (11) is transformed to become

$$\frac{\alpha}{\alpha_o} = e^{-b_o\gamma} \qquad (13)$$

The variation of γ with $\frac{C_o^t}{C_o^o}$ or $\frac{\alpha}{\alpha_o}$ is shown by the de-aeration curve in Fig. 1 of Ref. (4).

This variation has been tabulated in Table 3 thus the corresponding values of time may be calculated from equation (12) which can be written

$$t = \frac{\gamma}{A_o/V} = 152\ \gamma \text{ cm} \qquad (14)$$

where γ is given in min/cm.

The values of time for corresponding values of γ have also been tabulated in Table 3, while the variation of $\frac{\alpha}{\alpha_o}$ with t has been plotted in Fig. 1.

Equation (13) may be written in the form of equation (4)

$$\frac{\alpha}{\alpha_o} = e^{-\lambda_o t} + \mu_o \left(1 - e^{-\lambda_o t}\right) \qquad (15)$$

where

$$\lambda_o = \frac{A_o}{V} b_a \qquad (16)$$

and

$$\mu_o = o \ * \qquad (17)$$

b_a is the coefficient of exit for air, which for 20°C is

$$b_a = 0.534 \text{ cm/min} \qquad (18)$$

Thus from (10) and (18)

$$\lambda_o = \frac{0.534}{152} \text{ min}^{-1} = 0.0035 \text{ min}^{-1} \qquad (19)$$

λ is a measure of the speed of de-aeration. The greater the value of λ the quicker is the de-aeration as can be seen from the form of equation (4).

Comparing the value of λ for de-aeration under the stated hypothetical assumption with these of the experimental results shown in Table 2 we see that λ_o is much smaller than the values of λ from actual measurements. This means that the actual de-aeration of the water of the tunnel under any speed of the centrifugal pump is much quicker than the hypothetical de-aeration of the water through only the free surfaces of the water in the tanks, and that the speed of de-aeration increases as the rate of flow in the circuit is increased.

Now if we suppose that the mixing of the water is perfect in all the tests it is possible to find the total area of water gas interface having in mind that b_o and V are constant quantities.

From equation (16) it follows that:

$$\frac{A}{A_o} = \frac{\lambda}{\lambda_o} \qquad (20)$$

Where λ is given in Table 2 for the various speeds of the centrifugal pump and λ_o by equation (19).

From the above we can form Table 4 which gives the ratio $\frac{A}{A_o}$ for the various speeds of the pump tested.

5.2 Discussion of Table 4

The actual values of the ratio $\frac{A}{A_o}$ are greater than the corresponding values of this ratio given in Table 4 because the hypothetical de-aeration curve ($A = A_o$) has been plotted on the assumption that the de-aeration takes place under zero partial pressure of gases while for all the experimental curves the pressure of gases above the surface of the water was never less than 4 ft of water column.

---

* $\mu_o = o$ because it has been assumed that $P = o$.

Even under static conditions (0 rev/min) the total water-gas interface (A) in the circuit is more than 5 times greater than A_0. The ratio $\frac{A}{A_0}$ is probably larger than the given value in table 4 because the mixing of the water in this case is rather poor. The great difference between A and A_0 is evidently due to the presence of numerous gas bubbles of various sizes in the bulk of the water which under the low static pressure and by diffusion of gases dissolved in the water are increased in size and rise to the free surface of the water in the tanks with velocities corresponding to their size. In this case (0 rev/min) A is expected to reduce gradually with time for two reasons:

(a) the larger sized bubbles rise quicker to the surface and

(b) the total dissolved gas content of the water decreases with time and so the rate of diffusion of gases in solution into the bubbles is reduced with the result that the growth of bubbles becomes gradually slower.

When the centrifugal pump is made to operate, cavitation appears in the circuit, the intensity increasing as the rate of flow in the circuit is increased. The rapid increase of the ratio $\frac{A}{A_0}$ with the speed of the pump suggests that the de-aeration of the circuit is greatly affected by the cavitation intensity.

6. AERATION OF THE CIRCUIT WATER

6.1 Reabsorption of Travelling Bubbles

When there is a circulation of the water in the circuit the static pressure in the various regions of the circuit varies with variation of the rate of flow through them.

In the present circuit the maximum pressure appears in the tube connected to the discharge of the pump.

Let p_i be the absolute pressure in the discharge pipe of the pump, p_x the partial pressures of the gases in the gaseous space above the water in the tanks (in absolute units of pressure) and p_{atm} the atmospheric pressure. Also let α^* be the gas content of the water saturated under atmospheric conditions, α_x the gas content of the water saturated under the partial pressure of gases p_x, α_t the actual gas content of the water at time t and α_1 the gas content of water saturated at partial pressure of gases p_i.

Then by application of Henry's Law:

$$\frac{\alpha_x}{p_x} = \frac{\alpha^*}{p_{atm}} \quad \text{or} \quad \frac{\alpha_x}{\alpha^*} = \frac{p_x}{p_{atm}} \qquad (21)$$

and

$$\frac{\alpha_1}{p_i} = \frac{\alpha^*}{p_{atm}} = \frac{\alpha_x}{p_x} \qquad (22)$$

α_x represents the minimum value of dissolved gas content to which the water in the circuit will drop with continuous de-aeration under pressure p_x (theoretically at infinite time).

The ratio $\frac{\alpha_t}{\alpha_i}$ represents the degree of super-saturation ($\alpha_t > \alpha_i$) or undersaturation ($\alpha_t < \alpha_i$) of water of dissolved gas content α_t in a region of static pressure equal to p_i.

If the speed of the pump and the rate of flow are kept constant α_i remains constant if p_x is constant (because then p_i = const) while α_t gradually decreases with time. Therefore the ratio $\frac{\alpha_t}{\alpha_i}$ decreases as the de-aeration proceeds.

When α_t/α_i becomes smaller than unity the gas nuclei and/or gas bubbles are (depending on their size) partly or wholly dissolved in the water during their travel through the region of maximum pressure (region where $\alpha_t < \alpha_i$) this complete or partial reabsorption of the travelling gas nuclei and/or gas bubbles results in increasing the dissolved gas content in the region following the region of maximum pressure. The rate of reabsorption, expressed as amount of gases reabsorbed by the water through unit area of gas-water interface in unit time, will be a function of $\frac{\alpha_t}{\alpha_i}$ while the total amount of gases redissolved into the water will be a function of $\frac{\alpha_t}{\alpha_i}$, α_t and of the period of time which the gas nuclei and/or gas bubbles needs to travel through the maximum pressure region (region where $\alpha_t < \alpha_i$).

6.2 Method of Aeration

It was decided, for the sake of keeping the properties of the test water as closely as possible unaltered, that the water once introduced into the circuit should not be changed throughout the tests. However, after a certain number of tests the gas content of the water was very low. To prepare for the next series of tests the gas content should be increased to its desired maximum magnitude. For this purpose the following procedure was adopted.

The pressure on the top of the tanks was reduced to about 2 ft of water below atmospheric and the centrifugal pump was set to operate at a speed of about 2400 rev/min. Under these conditions a small amount of atmospheric air was continuously sucked into the circuit by a tapping in the pump section. Care was taken to limit the amount of air introduced into the circuit to prevent the impeller passages being blocked by air. By taking this precaution the absolute pressure in the discharge tube of the pump was nearly 2 atm (p_i = 2 atm. abs.). For this value of p_i the value of the ratio α_t/α_i was much smaller than unity even when the gas content of the water in the tanks (α_t) was about equal to α^*).

Under these conditions it was found that after 90 minutes of aeration the water in the tanks always had a gas content $\alpha_t > \alpha^*$. After the aeration of the water was completed the circuit was left open to the atmosphere over-night to give time for bubbles of a certain size and larger to rise to the surface of the water in the tank.

7. CONCLUSIONS

From these theoretical and experimental investigations it can be deduced that:

The de-aeration of the water in the circuit (found by experiment) is very quick and depends mainly on the speed of the pump. In fact for the higher range of speeds the gas content of the water may be reduced to about 50% of its original value in only 10 minutes.

The de-aeration of the water in the present circuit takes place mainly through the total area of the water-gas interface in the body of the water which includes the water-gas and/or vapour interface of the cavitation zones, the surface of the total number of travelling bubbles which are formed after the collapsing of the cavitation cavities, and from the surface of the total number of gas nuclei existing in the water.

A rough estimation of the total water-gas interface gives that for water standing still in the circuit the total water-gas interface is as large as 5 times the free surface of water in the tanks while when the water is circulating the total water-gas interface may become as large as 50 times the free surface of water in the tanks.

The water in the circuit can be aerated to supersaturation state in about 90 minutes ($\alpha_t > \alpha^*$).

Due to the very rapid de-aeration of the water the range of gas content is limited. Thus tests on the influence of gas content on the inception of cavitation can only be carried out over this limited range.

It is suggested that to increase the range of gas content within which experiments on cavitation may be undertaken, the water of the circuit should be saturated with some more soluble gas than atmospheric air. It is suggested that carbon dioxide be used.

ACKNOWLEDGEMENT

The work described was undertaken in the Aeronautics and Fluid Mechanics Department of the University of Glasgow under the guidance of Prof. W.J. Duncan and Dr. A.S. Thom, using equipment loaned by the Mechanical Engineering Research Laboratory. It is published by permission of the Dean of the Faculty of Engineering, University of Glasgow.

Distribution: Group 4.

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LIST OF TABLES

LIST OF FIGURES

TABLE 1

Mean pressures during de-aeration tests

Run	Rev/min	Mean total absolute pressure in gaseous space (ft of water)	Vapour pressure (ft of water)	Pressure of gases (ft of water)
1	2800	4.8	0.7	4.1
2	2500	4.8	0.7	4.1
3	2000	5.2	0.7	4.5
4	1500	5.3	0.7	4.6
5	1000	5.0	0.7	4.3
6	0	5.4	0.7	4.7

TABLE 2

Values of λ and μ at various pump speeds

rev/min	λ (min^{-1})	μ
0	0.018	0.615
1000	0.062	0.400
1500	0.064	0.380
2000	0.090	0.340
2500	0.102	0.300
2800	0.164	0.285

TABLE 3

Variation of γ with gas content

$\alpha = \frac{C_o\ t}{C_o\ o}\%$	γ (min/cm)	t (min)
100	0	0
90	0.2	30
80	0.4	60
70	0.7	106
60	1.0	152
50	1.35	205
40	1.75	266
30	2.30	350
20	3.10	470
10	4.50	685

TABLE 4

Ratio of actual interface area to tank surface area for various pump speeds

rev/min	λ (min^{-1})	$\frac{A}{A_o} = \frac{\lambda}{\lambda_o}$
0	0.018	5.15
1000	0.062	17.70
1500	0.064	18.30
2000	0.090	25.70
2500	0.102	29.20
2800	0.164	47.00

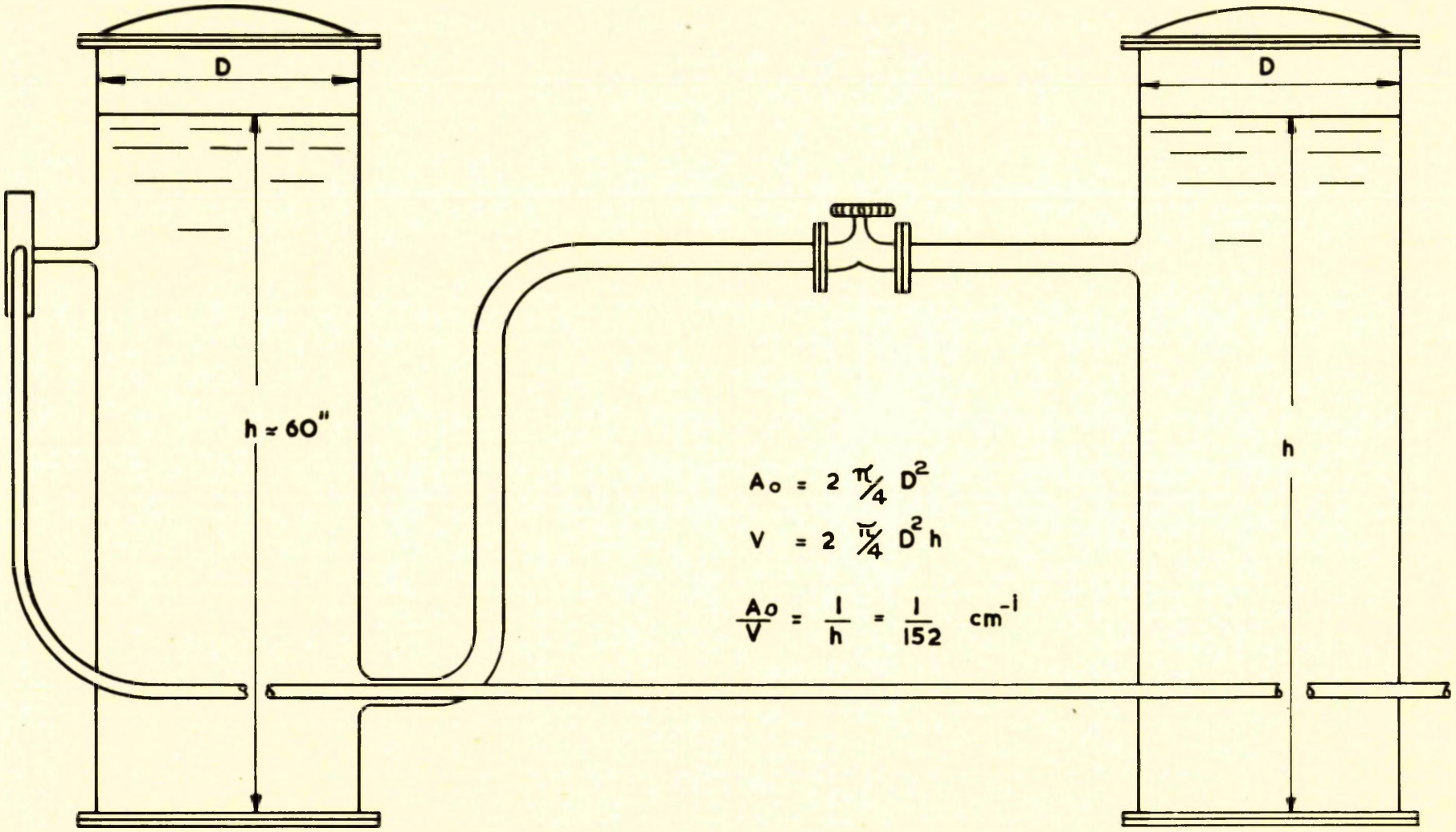


FIG. 1. CAVITATION CIRCUIT

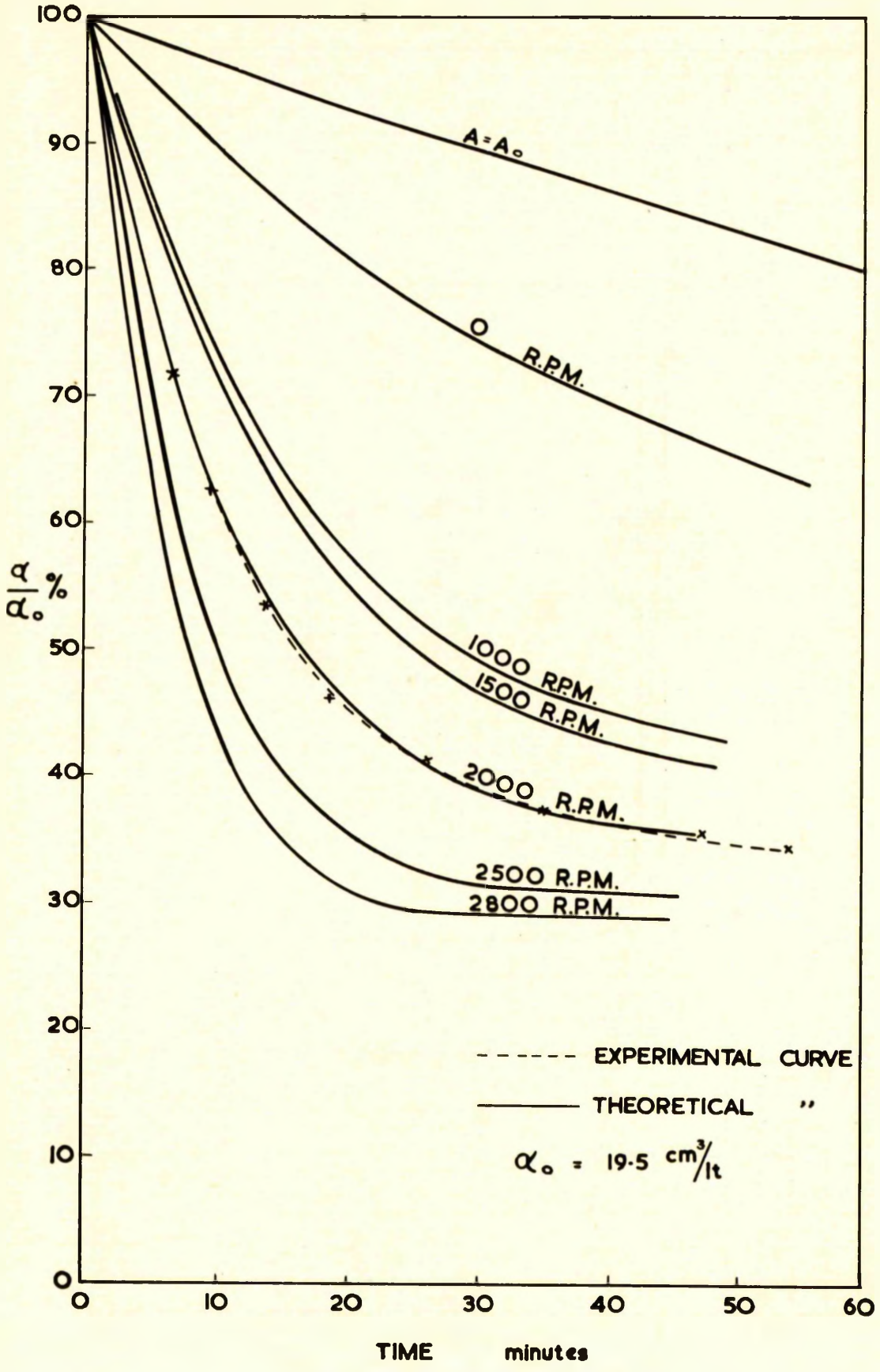


FIG. 2. DE-AERATION OF CAVITATION CIRCUIT

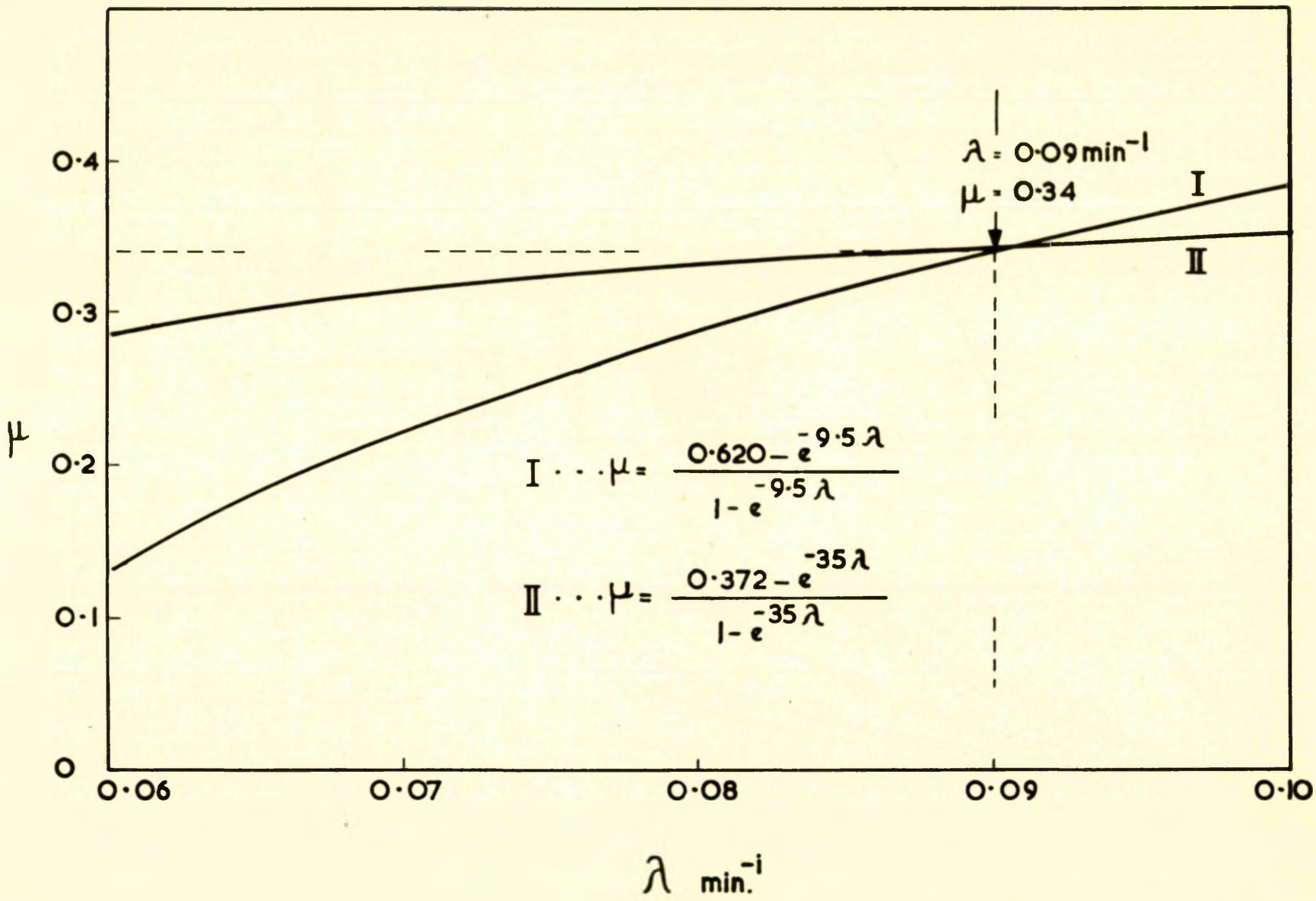


FIG. 3. VARIATION OF μ WITH TIME COEFFICIENT λ

APPENDIX VI

CALIBRATION OF THE VENTURI

The water supply used for the calibration of the venturi meter was taken from a large water reservoir on the top of the North Engineering Buildings (FIG. 1) During this calibration the level of water in the reservoir was maintained nearly constant and it was about 60 ft. above the level of the venturi.

The rate of flow of water through the venturi was adjusted by the downstream valve V. The water running for a given interval of time was collected in tank T and was weighed by the balance B. A schematical layout for the present calibration is shown in FIG. 1. In this figure ΔH represents the difference in levels of the mercury columns in the U tube caused by a given rate of flow.

Balance

The systematical error of the balance was -0.15 lbs. over the used range of weights.

In order to have the percentage of the systematical error nearly constant over the whole range of calibration the corresponding intervals of time given in TABLE I were calculated as a function of the rate of flow to be measured.

The present calibration covers the range of rate of flow from 0.0100 $ft^3/sec.$ to 0.0700 $ft^3/sec.$

TABLE I

Rate of flow $ft^3/sec.$		Time sec.
0.0100 - 0.0120	----------	300
0.0120 - 0.0160	----------	240
0.0160 - 0.0210	----------	190
0.0210 - 0.0320	----------	130
> 0.0320	----------	80

The result of the calibration has been tabulated in TABLE II with ΔH as defined in FIG. 1 and Q representing the rate of flow in cubic feet of water per second.

The variation of Q with ΔH can be written in the form of the following equation:

$$Q = K(\Delta H)^B \quad \ldots \quad (1)$$

from which

$$\log Q = \log K + B \log(\Delta H) \quad \ldots \quad (2)$$

or

$$\log Q = A + B \log(\Delta H) \quad \ldots \quad (3)$$

where A and B are constants.

Applying the method of least squares the values of A and B have been determined:-

$$A = -1.947 = \bar{2}.053 \quad \text{--------} \quad (4a)$$

$$B = 0.503 \quad \text{--------} \quad (4b)$$

Introducing the values of A and B from (4a) and (4b) to (3)

$$\log Q = \bar{2}.053 + 0.503 \log \Delta H \quad (5)$$

or

$$Q = 0.01132\, \Delta H^{0.503} \quad (6)$$

where Q in $ft.^3/sec$

and ΔH in inches.

Log Q has been plotted against $\log \Delta H$ in FIG. 2. In the same figure the actual experimental points have been plotted.

Limitations of the calibration:

The calibration of the venturi is valid only if the pressure at the venturi throat is higher than the critical pressure for the inception of cavitation. Cavitation appearance in the venturi imposes a limit to the pressure drop in its throat and

the cavity formation will change the effective cross section through which the water runs. Thus in case of cavitation in the venturi the present calibration is not valid.

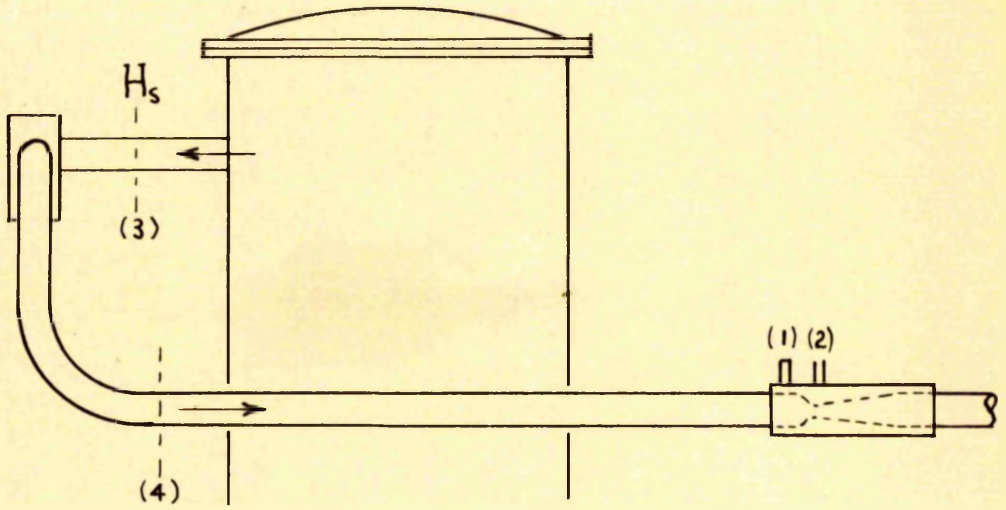


FIG. 3.

From FIG. 3 the absolute pressure (p_1) at tapping (1) of the venturi will be

$$p_1 = H_s + H_d - L_{4,1} \qquad (7)$$

where

H_s is the absolute pressure at section (3)

H_d is the manometric head of the pump,

and $L_{4,1}$ represents the friction losses between sections 4 and 1.

Now if ΔH is the difference in levels of the mercury columns in the U tube connected to tappings (1) and (2) of the venturi then from FIG. 1 it follows that

$$p_1 - p_2 = x_2 - x_1 - \frac{x_2 - x_1}{13.6} = (x_2 - x_1)\frac{12.6}{13.6}$$

or

$$p_1 - p_2 = 0.927\ \Delta H \qquad (8)$$

where $(p_1 - p_2)$ is given in inches of mercury column.

If $(p_1 - p_2)$ is expressed in feet of water column then equ. (8) is transformed to

$$p_1 - p_2 = 1.05\,\Delta H \quad \ldots \quad (9)$$

and the pressure in the throat of the venturi

$$p_2 = H_s + H_d - L_{4,1} - 1.05\,\Delta H \quad (10)$$

For cavitation-free flow through the venturi

$$p_2 > p_v \quad \ldots \quad (11)$$

where p_v is the vapour pressure of the water. Thus combining (11) and (10) for freedom from cavitation

$$H_s > p_v + 1.05\,\Delta H + L_{4,1} - H_d \quad (12)$$

Two limiting cases (a) and (b) will be examined as follows:

(a) Circulation of the water with the centrifugal pump operating at 1000 rev./min and the flow regulating valve fully opened.

From actual measurements we have:

p_v = 0.70 ft. of water.

ΔH = 3.4 inches.

$L_{4,1}$ = 0.45 ft of water.

and H_d = 5 ft of water.

Thus from (12) we get that for cavitation-free flow in this case we must have

$$H_s > -0.3 \text{ ft}$$

Apparently H_s is always positive and so in this case cavitation in the venturi cannot take place.

(b) Circulation of the water with the centrifugal pump working at its maximum speed of 2850 rev./min and with the flow regulating valve fully opened.

In this case

p_v = 0.70 ft of water,

ΔH = 31.3 inches

$L_{4,1}$ = 3.7 ft of water

and H_d = 37 ft of water.

Thus from (12) we obtain that for cavitation-free flow through the venturi we must have

$$H > 0.2 \text{ ft}$$

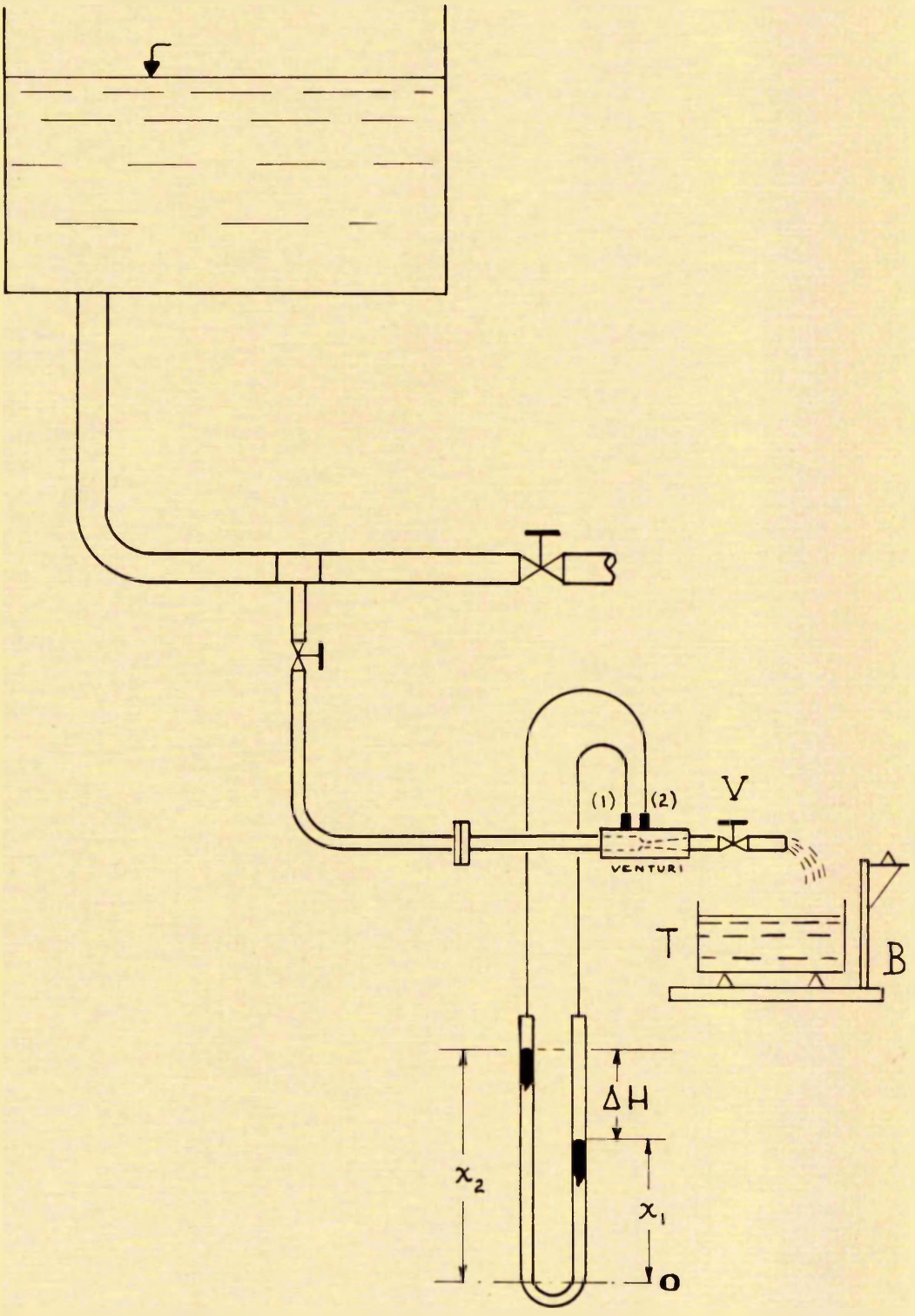
However in all the tests on cavitation in the pump H_s was never less than 1.5 ft of water. Therefore the venturi was always free from cavitation and the present calibration is valid.

CALIBRATION OF VENTURI

ΔH (ins)	Q ($ft^3/sec.$)	ΔH (ins)	Q ($ft^3/sec.$)	ΔH (ins)	Q ($ft^3/sec.$)
0.2	0.0050	6.2	0.0282	15.5	0.0449
0.4	0.0071	6.4	0.0287	16.0	0.0456
0.6	0.0087	6.6	0.0292	16.5	0.0463
0.8	0.0101	6.8	0.0296	17.0	0.0469
1.0	0.0113	7.0	0.0301	17.5	0.0476
1.2	0.0124	7.2	0.0305	18.0	0.0483
1.4	0.0134	7.4	0.0309	18.5	0.0490
1.6	0.0143	7.6	0.0314	19.0	0.0496
1.8	0.0152	7.8	0.0318	19.5	0.0504
2.0	0.0160	8.0	0.0322	20.0	0.0510
2.2	0.0168	8.2	0.0326	20.5	0.0515
2.4	0.0176	8.4	0.0330	21.0	0.0522
2.6	0.0183	8.6	0.0334	21.5	0.0528
2.8	0.0190	8.8	0.0338	22.0	0.0534
3.0	0.0197	9.0	0.0342	22.5	0.0541
3.2	0.0203	9.2	0.0345	23.0	0.0547
3.4	0.0209	9.4	0.0349	23.5	0.0554
3.6	0.0215	9.6	0.0353	24.0	0.0559
3.8	0.0221	9.8	0.0357	24.5	0.0565
4.0	0.0227	10.0	0.0360	25.0	0.0570
4.2	0.0233	10.5	0.0369	25.5	0.0576
4.4	0.0238	11.0	0.0378	26.0	0.0582
4.6	0.0243	11.5	0.0386	26.5	0.0588
4.8	0.0249	12.0	0.0395	27.0	0.0593
5.0	0.0254	12.5	0.0402	27.5	0.0598
5.2	0.0259	13.0	0.0410	28.0	0.0604
5.4	0.0264	13.5	0.0418	28.5	0.0610
5.6	0.0269	14.0	0.0426	29.0	0.0614
5.8	0.0274	14.5	0.0434	29.5	0.0620
6.0	0.0278	15.0	0.0442	30.0	0.0624

APPENDIX 6

FIG. 1.

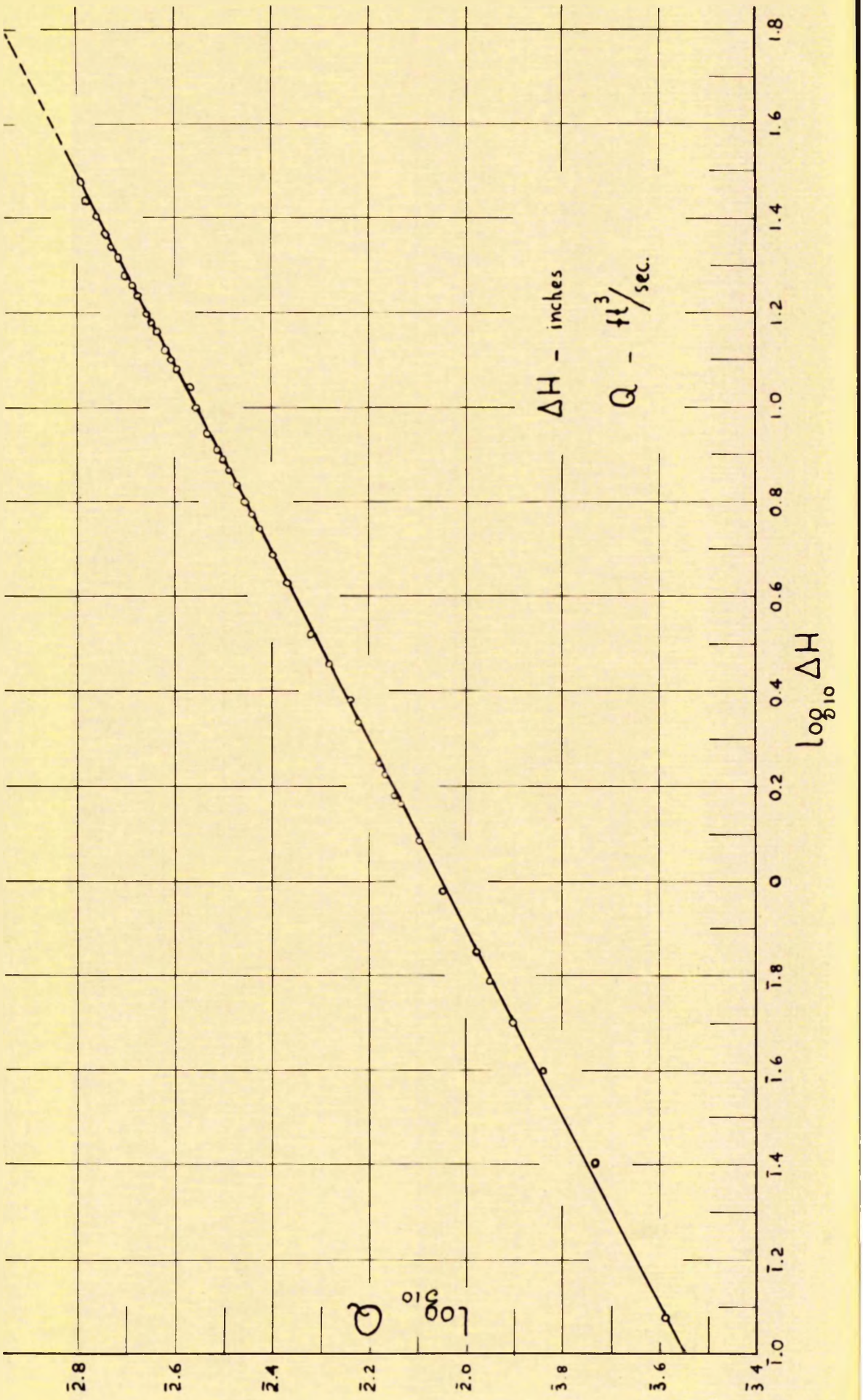


CALIBRATION OF THE VENTURI.

SCHEMATICAL LAYOUT.

APPENDIX 6

FIG. 2.



CALIBRATION OF THE VENTURI. Variation of Q with ΔH.

APPENDIX VII

CALIBRATION OF THE MOTOR

The motor used for turning the centrifugal pump was a D.C. Motor of 0.95 H.P.

The electrical wiring of the motor is shown in FIG. 1.

Resistors R_1 and R_2 were used for adjusting the speed of the motor. Resistor R_3 was used to compensate for the variation of the mains voltage supply. During the tests the mains voltage varied within the range 232 - 250 volts. By using R_3 it was possible, during the experiments, to keep the voltage across the motor constant at 230 volts.

For the calibration of the motor a spring balance was used to measure torque, and the motor speed was measured by a stroboscope.

For each speed the calibration curve is nearly a straight line, the equation of which, in a B.H.P, I plane, can be written:

$$B.H.P. = A + BI \quad \text{---------- (1)}$$

where B.H.P. is the brake horse power (motor output),

I is the indication of the ammeter

and A, B are constants depending on the speed of the motor.

A, B have been calculated by application of the method of least squares for each speed of the motor and their calculated values have been tabulated in TABLE I, while the corresponding curves have been plotted in FIG. 2.

TABLE I

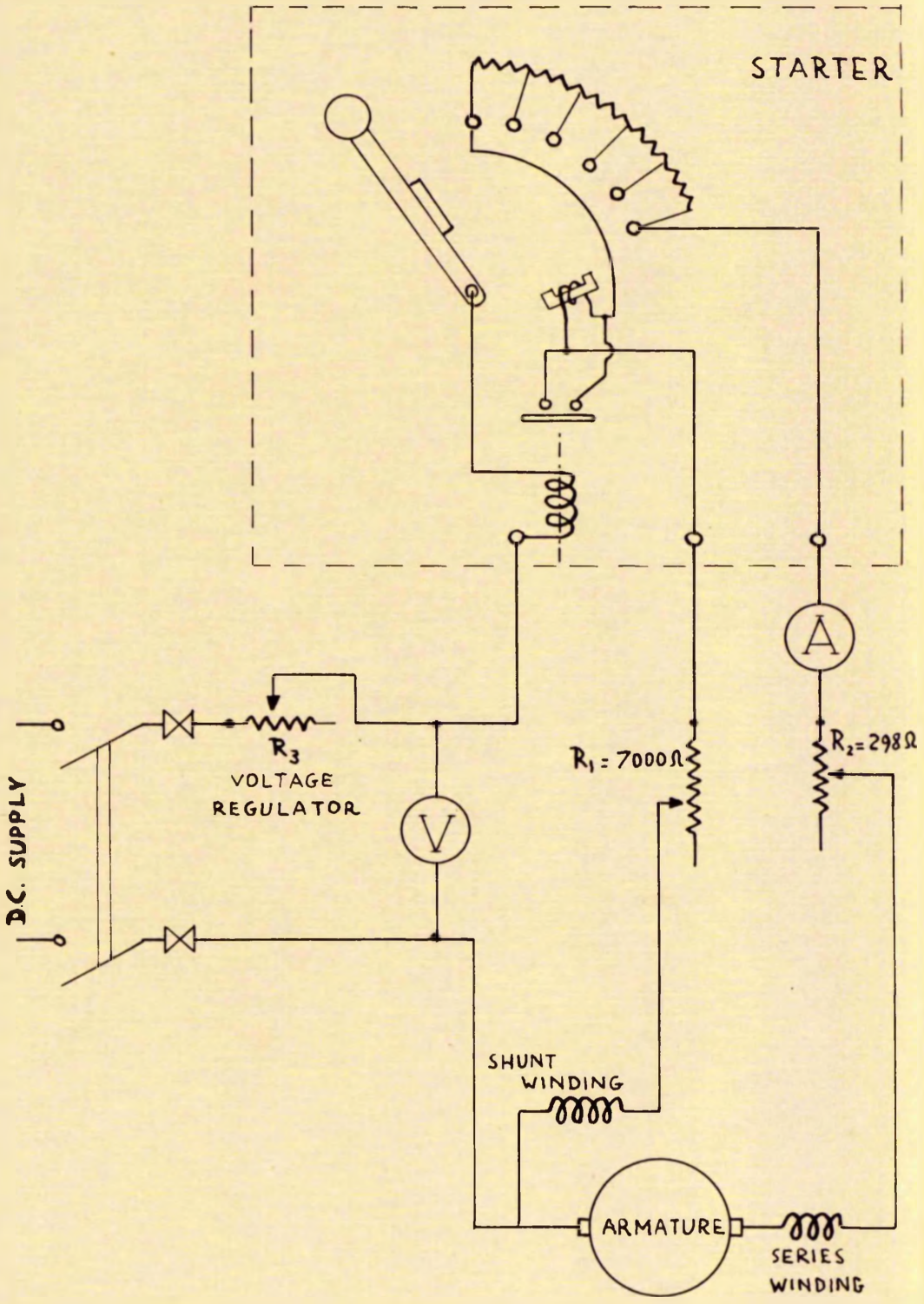
VALUES OF A and B

SPEED (R.P.M.)	A	B
1000	-0.0786	0.1146
1200	-0.0758	0.1325
1400	-0.0893	0.1506
1600	-0.1120	0.1790
1800	-0.1197	0.1968
2000	-0.1397	0.2165
2200	-0.1645	0.2372
2400	-0.1800	0.2602
2600	-0.1955	0.2785
2800	-0.2355	0.3040
3000	-0.2160	0.3100

CALIBRATION OF THE MOTOR

APPENDIX 7.

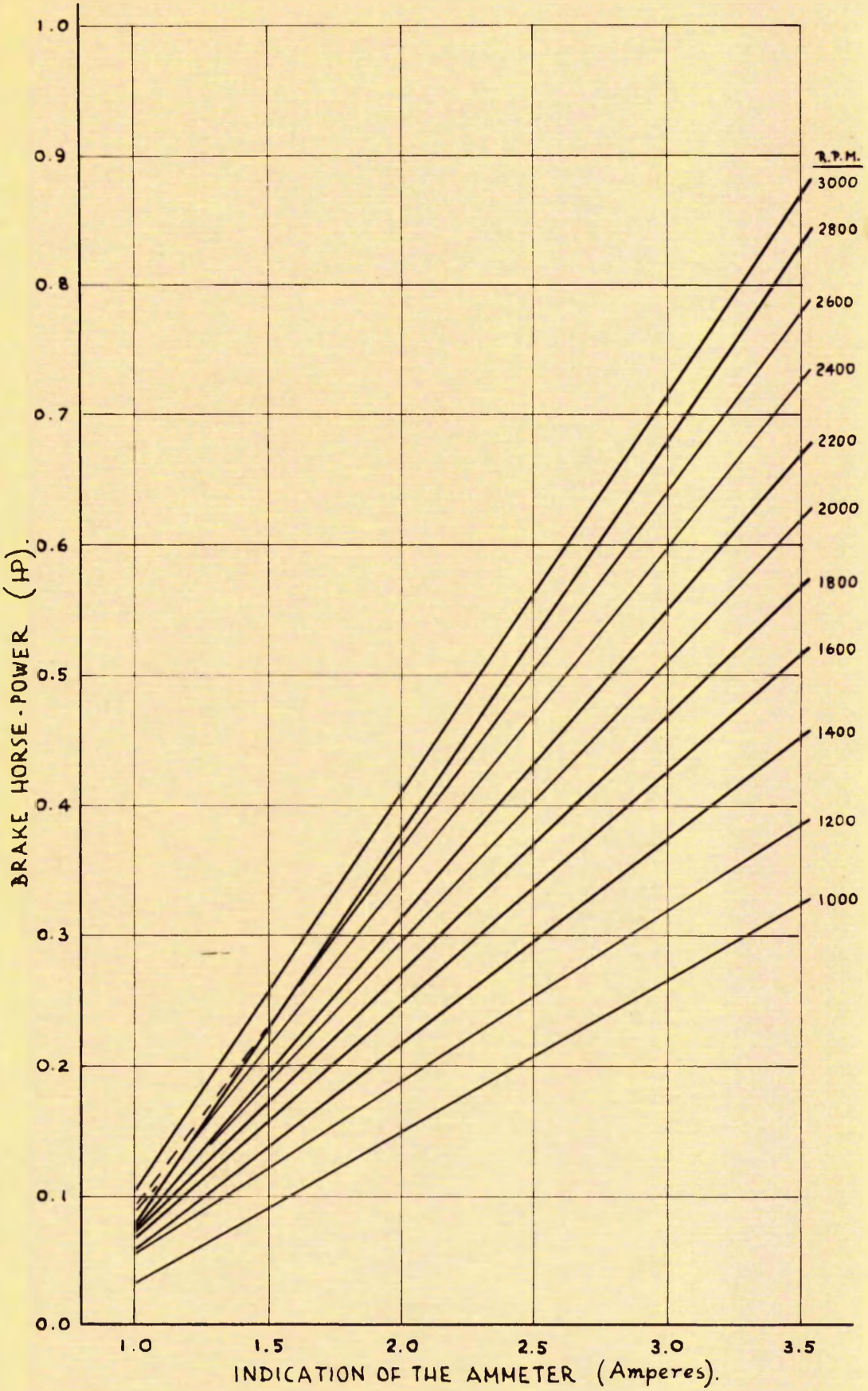
FIG. 1.



CIRCUIT DIAGRAM SHOWING CONNECTIONS TO D.C. MOTOR.

APPENDIX 7

FIG. 2.



CALIBRATION OF THE MOTOR. MEAN CURVES.

APPENDIX VIII

PERFORMANCE CHARACTERISTICS OF THE CENTRIFUGAL PUMP

The centrifugal pump is a standard pump (No. 22) manufactured by Messrs STUART-TURNER Ltd. The alterations made in the pump casing, and suction and discharge branches of the pump have resulted in considerable improvement of the original performance of the pump.

The performance characteristics of the pump for a number of speeds are shown in FIGS. 1 and 2.

In FIG. 1 the manometric head and efficiency of the pump have been plotted against capacity for 1000, 1250, 1500, 1750, 2000, 2200, 2450, 2650 and 2850 rev./min.

In FIG. 2 the variation of B.H.P. against capacity has been plotted for the same selection of speeds as above.

Dimensional Analysis of a Centrifugal Pump. Kanellopoulos (Ref.1)

The application of Dimensional Analysis to the performance of a centrifugal pump yields the following relations between the relative non-dimensional variables.

$$\frac{gH_d}{N^2D^2} = \varphi_1\left(\frac{Q}{ND^3}, R\right) \qquad (1)$$

$$\eta = \varphi_2\left(\frac{Q}{ND^3}, R\right) \qquad (2)$$

and

$$\frac{P}{\rho N^3 D^5} = \varphi_3\left(\frac{Q}{ND^3}, R\right) \qquad (3)$$

where

g is the body force due to gravity

H_d is the manometric head of the pump

N is the speed of rotation of the pump impeller

D is the diameter of the impeller

Q is the rate of flow through the pump

η is the efficiency of the pump

P is the brake-horse power

ρ is the density of the operating liquid

and R is the Reynolds number defined by the following relation:

$$R = \frac{\rho V D}{\mu} \qquad (4)$$

where

V is the tangential component of the absolute velocity at the outer circumference of the impeller (proportional to N)

and μ is the coefficient of viscosity of the fluid.

The influence of Reynolds number is usually small and is often neglected. In this case, equations (1), (2) and (3) become

$$\frac{g H_d}{N^2 D^2} = \varphi_1\left(\frac{Q}{N D^3}\right) \qquad (5)$$

$$\eta = \varphi_2\left(\frac{Q}{N D^3}\right) \qquad (6)$$

$$\frac{P}{\rho N^3 D^5} = \varphi_3\left(\frac{Q}{N D^3}\right) \qquad (7)$$

According to equ. (5) and for a given pump the curves $g H_d / N^2 D^2$ against Q / ND^3 for the various speeds of the pump should coincide. These curves have been plotted in FIG. 3. From this figure it seems that the head number against quantity number curves for the various speeds tested do not coincide and the departure is greater for smaller values of speed. This is due to the Reynolds number effect, the influence of which has been neglected in deriving equation (5).

On the other hand according to equ. (6), the curves of η against Q / ND^3 plotted for the various speeds of the pump should coincide, the best efficiency being the same for all speeds of

the pump. However the best efficiency varies with the speed, being smaller for lower speeds. This again is partly due to the Reynolds number effect. Davis (Ref. 2) states that the best efficiencies η_1 and η_2 under speeds N_1 and N_2 are related to the corresponding Reynolds numbers by an equation of the form:

$$\frac{1-\eta_1}{1-\eta_2} = \left(\frac{N_2}{N_1}\right)^{\gamma} = \left(\frac{R_2}{R_1}\right)^{\gamma} \qquad (8)$$

where R_1, R_2 are defined by equ. (4), and

γ is a number which depends on the type of the pump and on the Reynolds number, always decreasing with increasing R.

Shape number (Addison) and Specific speed of the present pump

The non-dimensional product which is called shape number for a pump is

$$N_S = \frac{N\sqrt{Q}}{(g H_d)^{3/4}}$$

where

N_s is the shape (Addison) number,

N is the speed of rotation of the pump

and Q and H_d are defined as the rate of flow and head of the pump correspondingly, at the condition of best efficiency operation of the pump.

Ns being non-dimensional is independent of the system of units adopted if a consistent system of units is always used, Duncan (Ref. 3).

For the present pump and for

N = 2850 rev./min. = $47.5\ /_{sec.}$,

Q = 0.0500 $ft^3/sec.$,

H_d = 44 ft of water

and g = 32.2 ft/sec^2,

we get by substituting these values in (9)

$$N_s = 0.047$$

Nevertheless, although the correct comparison of pumps should be by N_s the following parameter (N_s') called specific speed is widely used,

$$N_s' = \frac{N\sqrt{Q}}{H_d^{3/4}} \qquad (10)$$

where

N is given in rev./min,

Q in gallons per minute (g.p.m.),

and H_d in ft of water.

NOTE: N_s' is not a dimensionless product.

Its dimensions are

$$N_s' \equiv g^{3/4} N_s \equiv g^{3/4} \equiv (LT^{-2})^{3/4} \equiv L^{3/4} T^{-3/2}$$

For the present pump and for

N = 2850 rev./min.

Q = 18.7 g.p.m.,

H_d = 44 ft.

Thus

$$N_s' = 710 \; \frac{(gal)^{1/2}}{(min)^{3/2}\,(ft)^{3/4}}$$

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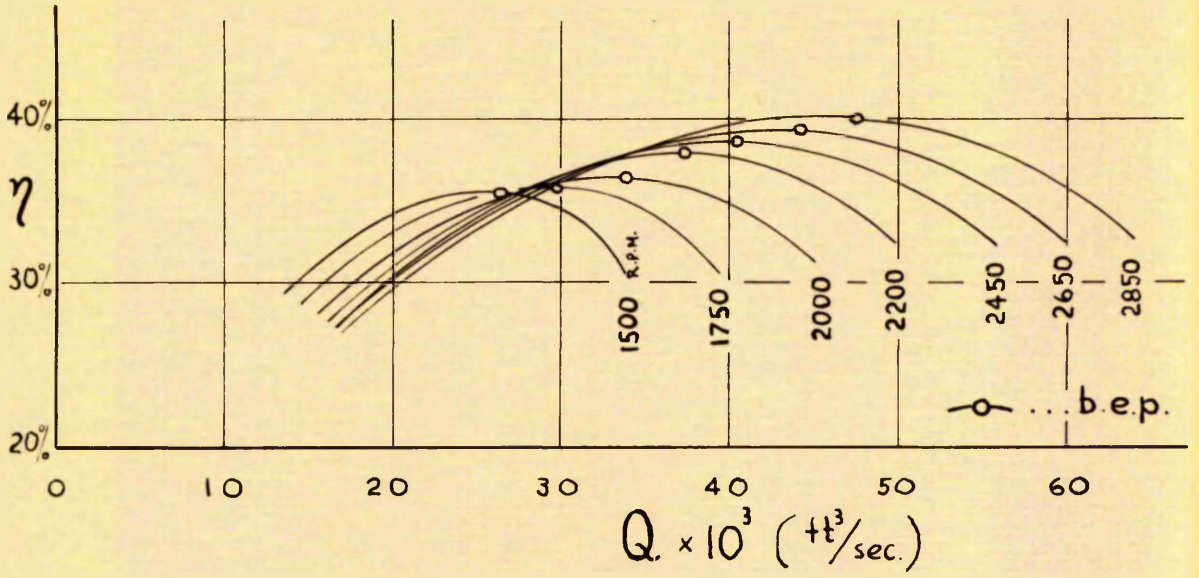
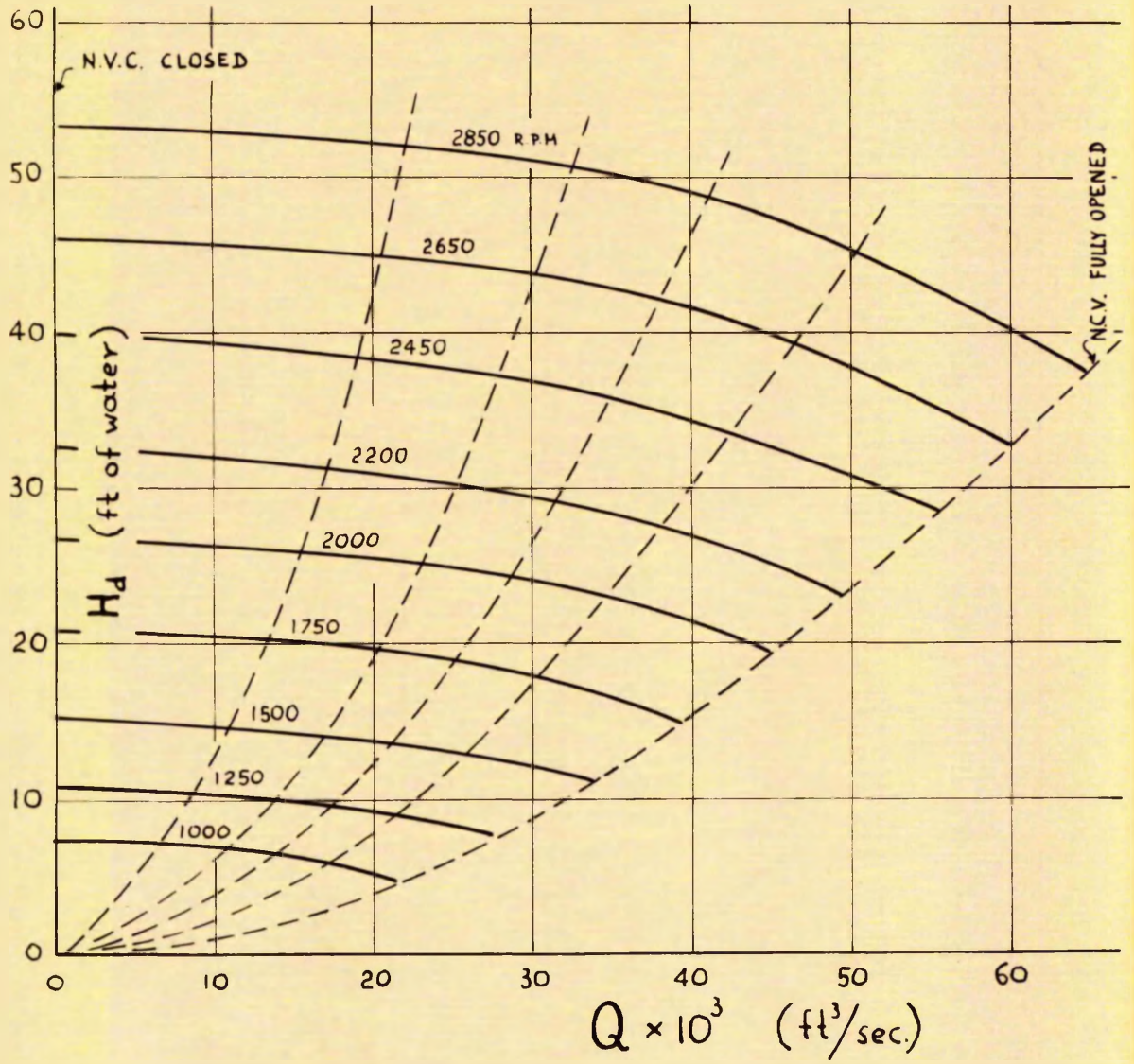
FIG. 1.



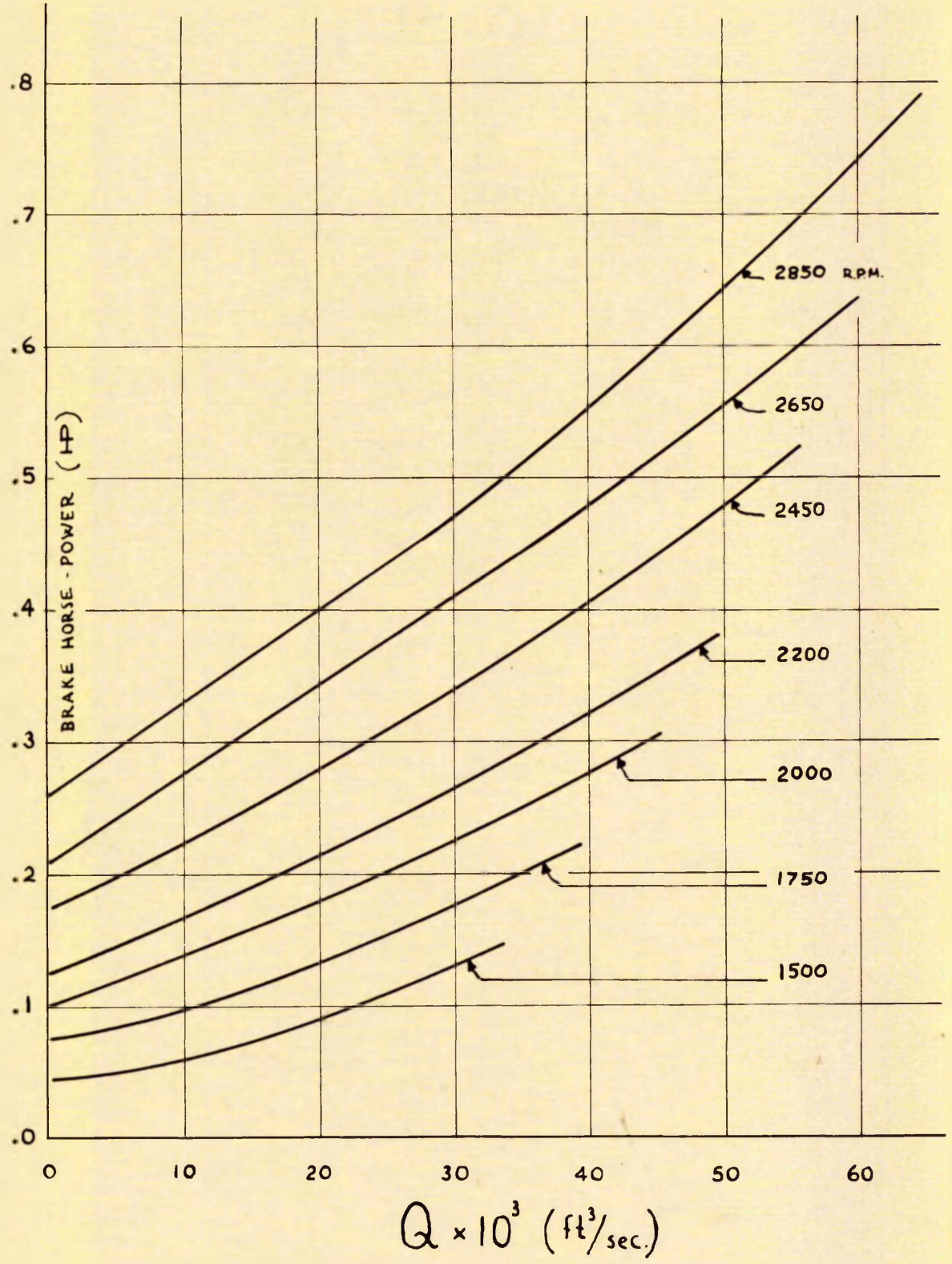


PERFORMANCE CHARACTERISTICS OF THE PUMP.

Variation of H_d and η with Q.

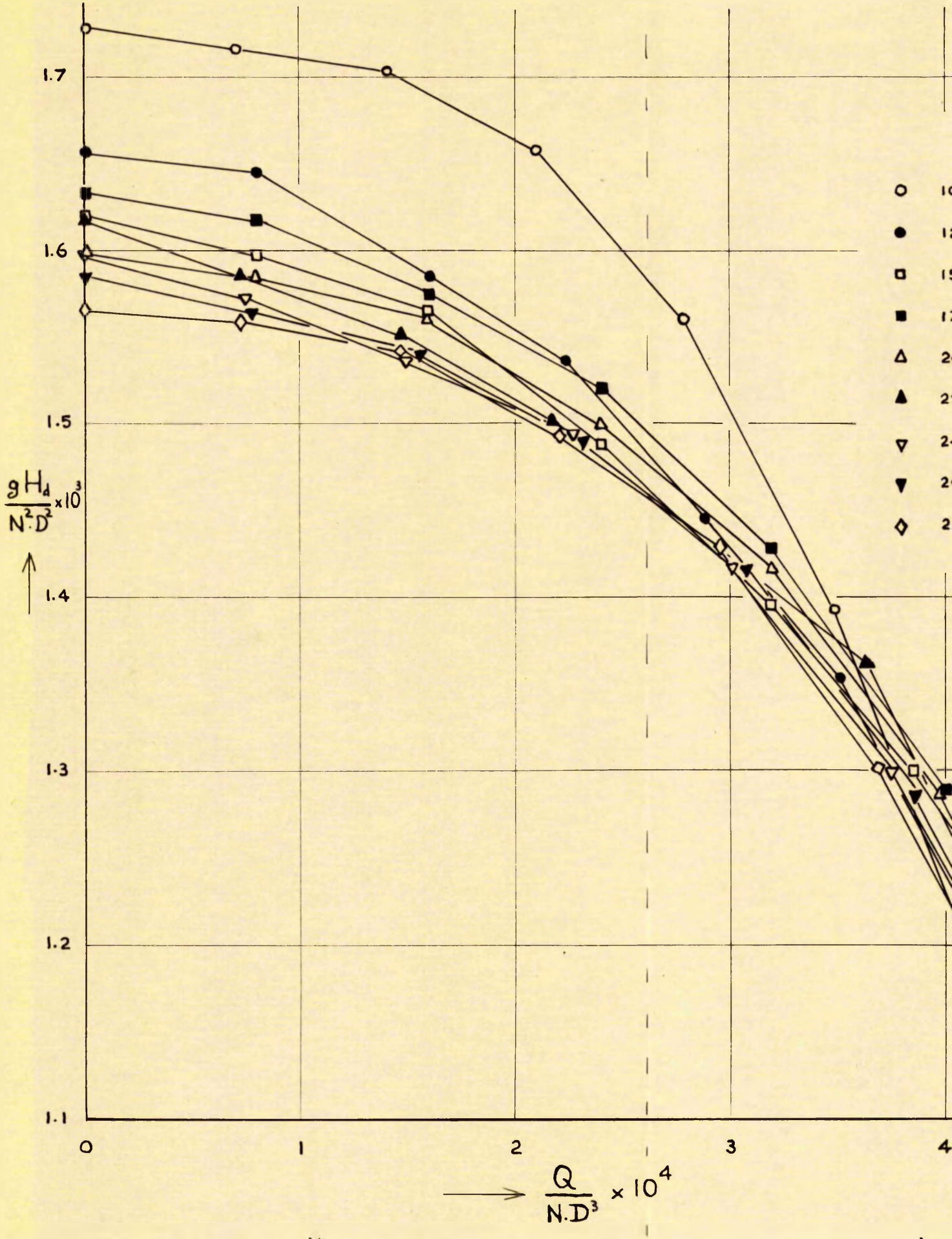
APPENDIX 8

FIG. 2.



PERFORMANCE CHARACTERISTICS OF THE PUMP

Variation of B.H.P. with Q.



Variation of gH_d/N^2D^2 with $Q/N.D^3$. (REYNOLDS NUMBER EFFECT)